GLOSSARY OF OPTICAL PROPERTIES
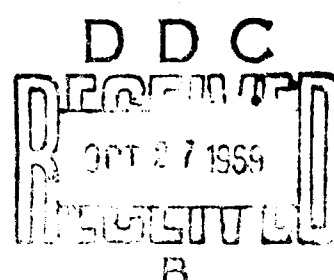
AD695479

RICHARD I. AKAWIE
SHELDON J. WELLES

ELECTRONIC PROPERTIES INFORMATION CENTER

IRNEE J. D'HAENENS

HUGHES RESEARCH LABORATORIES

D D C

RECEIVED
OCT 2 7 1969
B

S-10

FEBRUARY 1969

E LECTRONIC
P ROPERTIES
I NFORMATION
C ENTER

EPIC

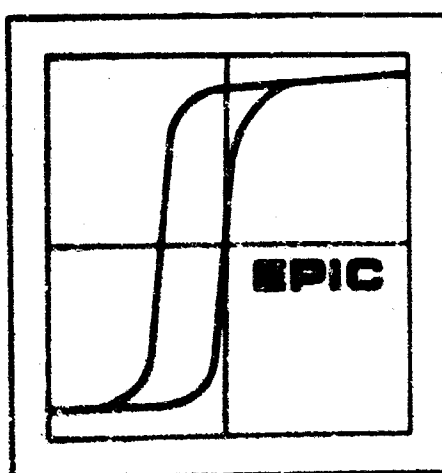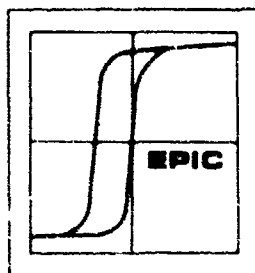# GLOSSARY OF OPTICAL PROPERTIES

RICHARD I. AKAWIE
SHELDON J. WELLES

ELECTRONIC PROPERTIES INFORMATION CENTER

IRNEE J. D'HAENENS

HUGHES RESEARCH LABORATORIES

E LECTRONIC
P ROPERTIES
I NFORMATION
C ENTER

EPIC

FOREWORD

This report was prepared by Hughes Aircraft Company, Culver City, California, under Contract Number F33615-68-C-1225. The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. R.F. Klinger, Project Engineer.

The Electronic Properties Information Center (EPIC) is a designated Information Analysis Center of the Department of Defense authorized to provide information to the entire DoD community. The purpose of the Center is to provide a highly competent source of information and data on the electronic, optical and magnetic properties of materials of value to the Department of Defense. Its major function is to evaluate, compile and publish the experimental data from the world's unclassified literature concerned with the properties of materials. All materials relevant to the field of electronics are within the scope of EPIC: insulators, semiconductors, metals, super-conductors, ferrites, ferroelectrics, ferromagnetics, electroluminescents, thermionic emitters and optical materials. The Center's scope includes information on over 100 basic properties of materials; information generally regarded as being in the area of devices and/or circuitry is excluded.

The Center provides a technical answering service in which the technical staff responds to inquiries ranging in complexity from simple requests for data point values to requests for comprehensive reviews of the literature. This service is available without charge to U.S. Government agencies, their contractors, subcontractors, suppliers, and those in a position to support the defense effort. Inquiries may be directed to:

Electronic Properties Information Center
Hughes Aircraft Company
Bldg. 6: E-175
Centinela & Teale Streets
Culver City, California 90230
Telephone: (213) 391-0711 Ext. 6596

The EPIC Bulletin, published quarterly, announces new publications and current activities of the Center. Users may request receipt of the Bulletin on a regular basis.

This report consists of an optical properties glossary together with an associated properties cross reference list. The authors wish to acknowledge the supporting assistance of other members of the EPIC staff, in particular, Miss Louise Croce.

iii

ABSTRACT

A glossary of optical property indexing terms used by the Electronic Properties Information Center is presented. Twenty eight primary optical property descriptors and over 180 related terms are carefully defined. A detailed list of property cross references provides a complete index to the glossary.

This report has been reviewed and is approved for publication.

Sheldon J. Welles

Dr. Sheldon J. Welles, Head
Electronic Properties Information Center

E.F. Smith

E.F. Smith
Project Manager

TABLE OF CONTENTS

INTRODUCTION

In collecting and indexing experimental data concerning the properties of materials to form an efficient retrieval system, it is essential that the indexing vocabulary be clearly defined. It is important that those performing the indexing have a clear and common understanding of the properties being indexed; it is equally important that users of the resultant retrieval system know how the information and data were indexed and the rational for the decision. To accomplish this dual objective, the Electronic Properties Information Center, prepared in January 1965, a Glossary of Electronic Properties (EPIC Report No. S-7), representing all electronic, magnetic, and optical property indexing terms used by the Center. Primary optical property terms included in this Glossary were ABSORPTION, PHOTON EMISSIVITY, PHOTON LUMINESCENCE, REFLECTION COEFFICIENT AND REFRACTIVE INDEX.

In 1968, the Electronic Properties Information Center expanded its scope to include increased coverage of the optical properties of materials. Emphasis was placed on solid-state laser materials, including doped glasses, doped crystals and semiconductors, electro- and magneto-optic materials, and infrared transmitting materials. To accommodate this expanded scope, the Center has increased the number of optical property descriptors used in indexing. This Glossary of Optical Properties carefully defines these new descriptors and, at the same time, defines, in a more comprehensive manner, the primary optical property descriptors included in the earlier Glossary of Electronic Properties.

The definitions contained in this Glossary go beyond a bare statement of the optical properties being observed; they attempt to provide enough qualitative understanding of the phenomena involved to effect correct interpretation of indexing and the retrieval of pertinent information or data.

The Glossary is divided into sections, in general, corresponding to those primary optical property descriptors under which data are indexed by the Center. Each of these primary descriptors is defined completely within its section. In addition, other primary descriptors and terms related to the primary descriptors are defined. All related terms and primary descriptors are underlined in the text at the point where they are most clearly defined. The relationship between the related terms and the primary descriptors is presented in the properties cross reference section of the Glossary, where the primary descriptors are given in capital letters. These cross references provide a complete index to the glossary.

1

ABSORPTION

When light (or other electromagnetic radiation) propagates through a material it undergoes two types of attenuation: absorption and scattering. The absorption coefficient α of the material is defined by Bouguer's law or Lambert's law:

$$I = I_o \, e^{-\alpha \ell} \, ,$$

where I_o is the intensity of the incident light and I is the light intensity after passing through ℓ, the thickness of the absorbing layer. When ℓ is measured in cm, α is expressed in cm^{-1}. When scattering is the primary attenuation mechanism present, α is called the scattering coefficient. If both absorption and scattering are present, α is called the total absorption coefficient. The extinction coefficient κ is given by the relation

$$\kappa = \frac{\alpha \lambda}{4 \pi} \, ,$$

where λ is the wavelength in vacuum. The extinction coefficient is a dimensionless quantity.

The transmittance T is defined as the fraction of incident light transmitted through the material, just as the absorptance A and the reflectance R represent the fractions absorbed and reflected, respectively, where

$$A + T + R = 1.$$

Considering different reflections at both surfaces of the material, as shown in Figure 1, and neglecting multiple reflection inside the material, the transmittance is given by

$$T = I/I_o = (1-R)(1-R')e^{-\alpha \ell}.$$

3

ABSORPTION

The terms <u>transmissivity</u> and <u>absorptivity</u> refer to intrinsic material properties. Transmissivity is the transmittance for a unit thickness sample; absorptivity is equal to the absorptance of a material when that material has an optically smooth surface and is sufficiently thick to be opaque.
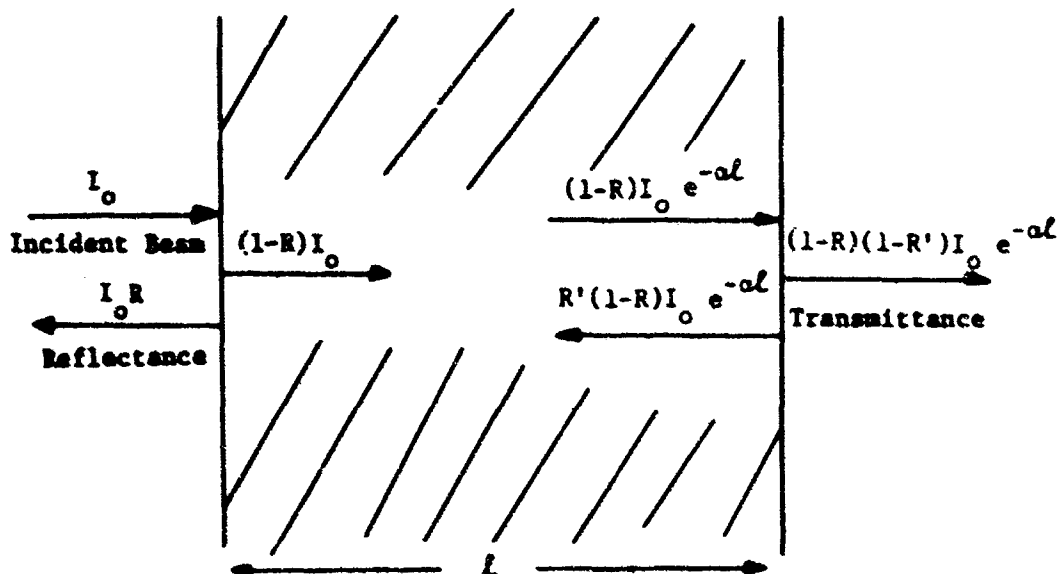

Fig. 1. Transmission of light through a material.

A plot of the absorption coefficient as a function of photon energy or wave-length constitutes the <u>absorption spectrum</u> of the material. Such spectra display certain distinctive features characteristic of the various mechanisms responsible for the absorption. Optical absorption phenomena are frequently used to determine the band structure of solids, particularly semiconductors. A feature of the optical absorption spectrum common to all semiconductors is the rapid increase in absorption which occurs over a small energy range when the incident radiation has an energy approximately equal to the energy gap E_g of the semiconductor. This is called the <u>absorption edge</u> or <u>fundamental absorption edge</u> of the material (Figure 2). This large increase in absorption is due to optically induced electron transitions from the valence band across the forbidden energy gap to the conduction band. If the

maximum energy of the valence band occurs at the same point in $\vec{k}$ - space as the mini-mum energy of the conduction band, the electron transition is a <u>direct transition</u>. If the k values are different, the transition is an <u>indirect transition</u>. Indirect tran-sitions involve the simultaneous interaction of the electrons with the electromagnetic radiation and lattice vibrations (phonons), while direct transitions involve only the interaction between electrons and the radiation.

Because of the mutual attraction of electrons and holes, it is possible for stable bound states of the two particles to be found. These excitations are called excitons. Since the photon energy required to create an exciton state from a filled valence band is less than the energy gap, absorption due to excitons or <u>exciton absorption</u> may be observed on the long-wavelength side of the fundamental absorption edge. In addition, the spectral variation for exciton absorption at energies greater than E_g is modified from that due to band-to-band absorption.
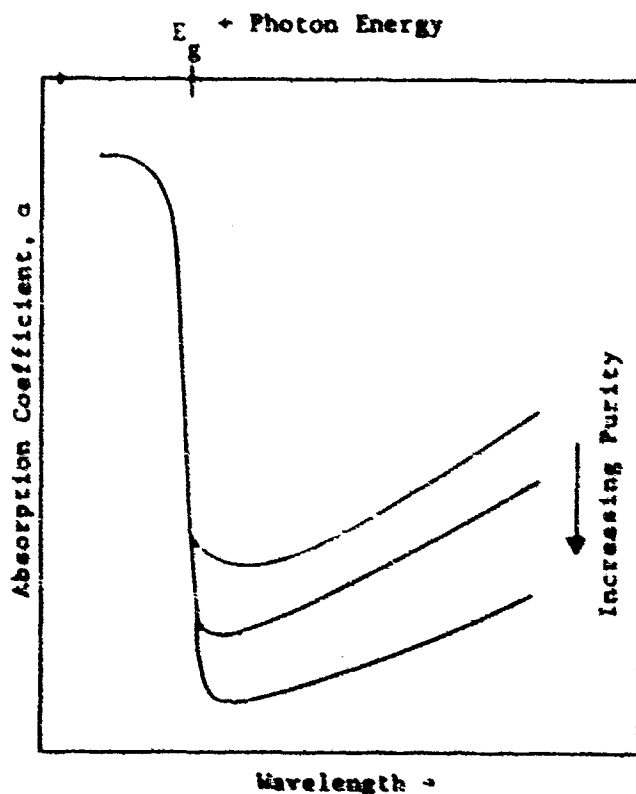

Fig. 2. Variation of absorption with wavelength near the fundamental absorption edge for semiconductor specimens of varying purity.

ABSORPTION

A material is said to have an <u>absorption line</u> at the frequency ν_o when parallel light from a source emitting a continuous spectrum is transmitted through the material with a frequency distribution similar to that depicted in Figure 3.
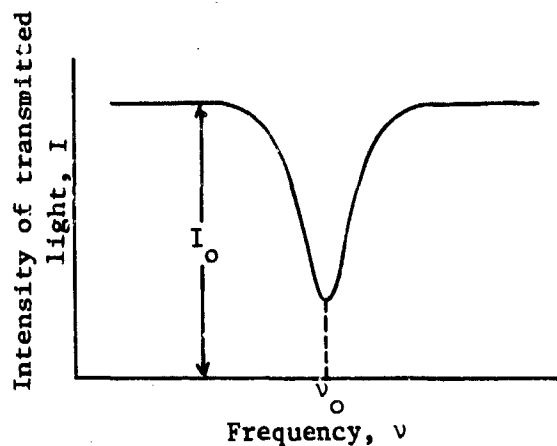

Fig. 3. An absorption line.

The variation of the absorption coefficient with frequency in an absorption line is shown in Figure 4. The <u>linewidth</u> of the absorption line, $\Delta\nu$, is defined as the full width at half of maximum α.
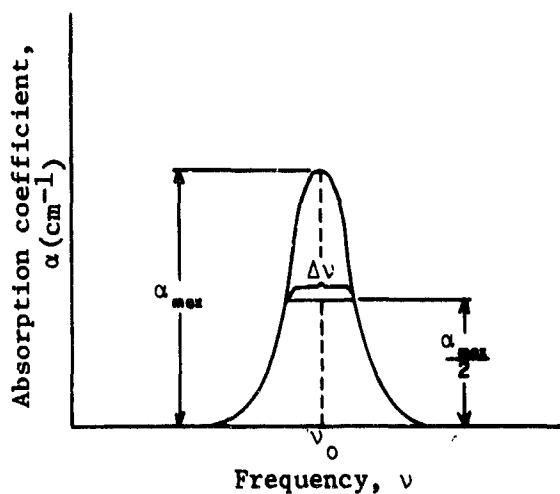

Fig. 4. Variation of absorption coefficient with frequency in an absorption line.

6

ABSORPTION

On an energy level diagram the absorption of each photon from the light beam raises atoms of the material from energy level 1 to energy level 2 (Figure 5). The difference in the energies of the two levels is given by

$$\Delta E = h\nu \; ,$$

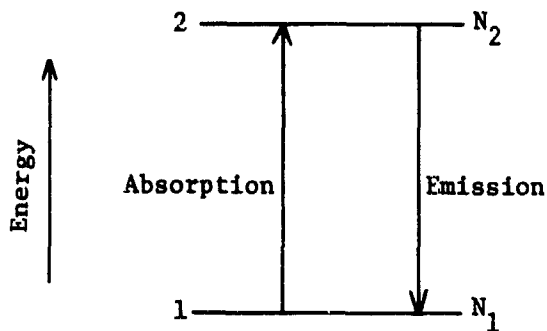where h is Planck's constant and ν is the optical frequency of the light.

Fig. 5. Absorption on an energy level diagram.

In general, the absorption coefficient of a material can be expressed in terms of the relevant energy level population densities N_1, N_2, and σ, the cross section for the transition (see transition cross section):

$$\alpha = (N_1 - N_2)\sigma.$$

In this expression, $N_1\sigma$ is the proper absorption coefficient, whereas $-N_2\sigma$ represents negative absorption. In a laser, the system is prepared so that $N_2 > N_1$ (population inversion) and, instead of being attenuated on passing through the material, the light beam is amplified. Since $N_2 > N_1$, we can define the gain of a laser material as

$$\text{gain} = I/I_o = e^{-\alpha\ell} = e^{(N_2 - N_1)\sigma\ell} \; ,$$

where ℓ is the length of the light path in the material. If the gain is sufficient to overcome circuit losses, the system will oscillate (see Laser Properties).

The Brillouin effect, or spontaneous Brillouin scattering, is the nonlinear, inelastic scattering of monochromatic light by elastic waves (acoustic phonons) in optically transparent materials. This effect is similar to Raman scattering (see Raman Effect), except that the role of the optic phonon in the Raman effect is taken over by an acoustic phonon in the Brillouin effect.

The Brillouin effect may be described as the diffraction of a light wave by a variable index of refraction grating, set up by the acoustic vibration. The incident light wave with wave vector $\vec{k}_o$ and frequency ν_o interacts with an acoustic wave with wave vector $\vec{q}$ and frequency Ω to give a light wave with wave vector $\vec{k}_1$ and frequency ν_1. Conservation of momentum and energy between the incident photon $(\vec{k}_o,\nu_o)$, the scattered photon $(\vec{k}_1,\nu_1)$, and the phonon $(\vec{q},\Omega)$ requires

$$\vec{k}_1 = \vec{k}_o \pm \vec{q} \ ,$$

and
$$\nu_1 = \nu_o \pm \Omega \ .$$

The plus sign in the above equations corresponds to Brillouin scattering in which acoustic energy is absorbed; the frequency of the scattered light is larger than the incident light (Figure 6a). The minus sign corresponds to emission of acoustic energy; the frequency of the scattered light is smaller than the incident light (Figure 6b).
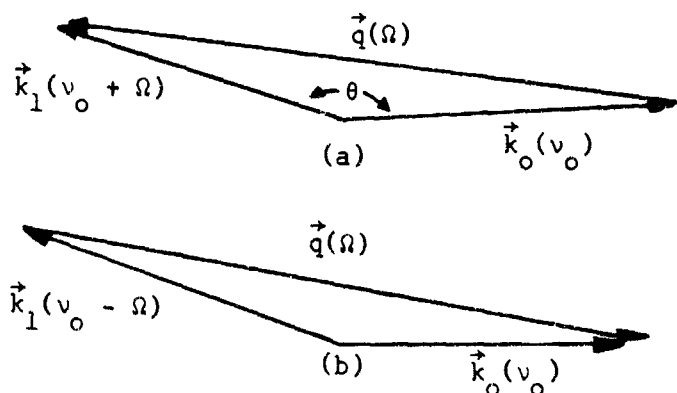

Fig. 6. Brillouin scattering. (a) acoustic energy absorbed. (b) acoustic energy emitted.

BRILLOUIN EFFECT

As shown in Figure 7, a typical spectrum of the scattered light consists of a triplet. The center line (Rayleigh line) has the same frequency as the incident light and corresponds to elastic Rayleigh scattering (see Scattering). The lines of lower frequency (Stokes line) and higher frequency (anti-Stokes line) differ from the center line by a frequency shift $\Delta\nu$ (Brillouin shift) whose magnitude is equal to the frequency of the effective phonon Ω. The Stokes and anti-Stokes lines are also known as Doppler components of the scattered light spectrum. The Brillouin effect in isotropic solids can give rise to two pairs of Stokes and anti-Stokes lines, one longitudinal pair and one transverse pair. In anisotropic solids it is possible to observe one longitudinal pair and two transverse pairs of lines.
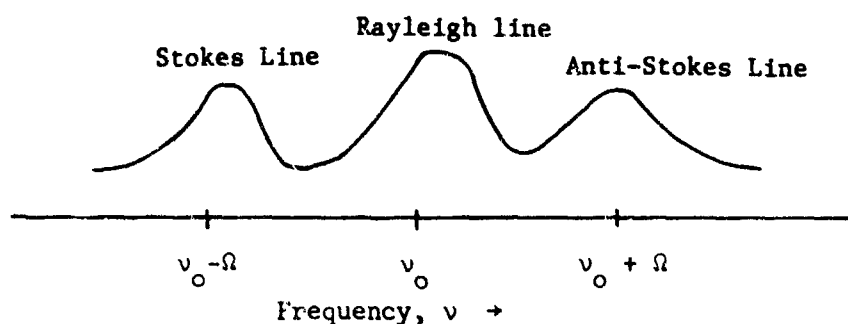
Fig. 7. Brillouin spectrum.

The momentum triangles, shown in Figure 6, may be considered to be isosceles, with $|\vec{k}_o| = |\vec{k}_1| \equiv k$. It follows that

$$q = 2 \, k \, \sin \frac{\theta}{2} \quad ,$$

where θ is the angle of scattering of the light. Since $q = 2\pi\Omega/V$ and $k = 2\pi n\nu/c$, the Brillouin shift $\Delta\nu$ can be expressed as

$$\Delta\nu = \Omega = \frac{2n\nu V}{c} \, \sin \frac{\theta}{2} \quad ,$$

10

BRILLOUIN EFFECT

where

        n = refractive index of the scattering medium

        c = velocity of light in vacuum

        V = velocity of acoustic waves (sound) in the scattering medium.

According to this equation, if the incident light is monochromatic and θ well defined, the measured Brillouin shift can be used to calculate the velocity of sound in the scattering medium. The maximum acoustic frequency that can be involved in Brillouin scattering is obtained for backward scattered light, $\theta = \pi$.

The stimulated Brillouin effect is similar to the stimulated Raman effect, except that the role of the optic phonon is taken over by an acoustic phonon. A giant pulse from a Q-switched laser, which exceeds the threshold of the scattering material, is required to form a coherent, highly directional beam in the backward direction. Many orders of Stokes and anti-Stokes lines are produced. As in the case of the spontaneous Brillouin effect, the velocity of sound in the scattering material can be determined. The stimulated effect has been observed in solids, liquids, and gases.

COTTON-MOUTON EFFECT

The Cotton-Mouton effect, or magnetic double refraction, is demonstrated by an isotropic material in a static magnetic field which becomes birefringent to light passing through it in a direction perpendicular to the magnetic field. The material may be a liquid or a solid. The effect is attributed to an orientation of magnetically anisotropic molecules in the field direction and is the magnetic analog of the electro-optic Kerr effect. Since thermal agitation interferes with this orientation, the effect decreases with increasing temperature, especially in liquids.

As with naturally birefringent materials, the incident light beam is split into two beams which are polarized perpendicularly to each other. The difference in the refractive indices parallel ($n_{\parallel}$) and perpendicular ($n_{\perp}$) to the magnetic field is proportional to the square of the magnetic field:

$$n_{\parallel} - n_{\perp} = C \lambda H^2 \quad ,$$

where C is the Cotton-Mouton constant, λ is the wavelength of the light in vacuum, and H is the magnetic field intensity. Since the two waves travel with different velocities, the resulting phase difference Γ between them as they leave the material can be measured and the Cotton-Mouton constant calculated:

$$\Gamma = \frac{n_{\parallel} - n_{\perp}}{\lambda} \ell = C \ell H^2 \quad ,$$

where ℓ is the length of the light path through the material.

The double refraction of light passed through a vapor in a direction perpendicular to a static magnetic field is known as the Voigt effect. In practice, the terms Cotton-Mouton effect and Voigt effect are used interchangeably in the literature. In magneto-optical experiments, the term Voigt configuration is used to describe incident radiation propagating perpendicular to the externally applied magnetic field.

13

ELECTRO-OPTIC EFFECT

The electro-optic effect is a change in the refractive properties of a material induced by an electric field. The effect in crystals is brought about by a displacement of the lattice resulting in modification of the electronic polarizability (or refractive index), as well as a direct modification of the electronic polarizability without lattice displacement. The effect in liquids and gases is due to alteration of existing electric moments in polar molecules or to creation of electric moments in non-polar molecules, followed by orientation of the molecules.

When the effect is found to be proportional to the square of the electric field, it is known as the Kerr effect (or electro-optic Kerr effect). If the effect is directly proportional to the electric field, it is called the Pockels effect (or linear electro-optic effect). The Kerr effect has been observed in gases, liquids, and solids, while the Pockels effect occurs in crystals only. Both effects have been observed in potassium tantalate niobate, in which the Kerr effect if found above the Curie temperature and the Pockels effect below the Curie temperature.

It is convenient to consider the change in $1/n^2$, with application of an electric field E, rather than a change in n directly, where n is the refractive index. The quantity $1/n^2$ can be written

$$\frac{1}{n^2} = \frac{1}{n_o^2} + rE + gE^2 + \dots \,,$$

where n_o is the refractive index in the absence of the field, and r and g are the linear and quadratic electro-optic coefficients, respectively. Crystals with negligible quadratic coefficients g show the Pockels effect, whereas those with no linear coefficients r show the Kerr effect.

For the Kerr effect to be observed in a crystal, it must have a center of symmetry. Only noncentrosymmetric crystals show the Pockels effect. Twenty-one of the 32

15

crystal symmetry classes do not contain centers of symmetry, and of these, 20 may exhibit the Pockels effect. These are the same 20 symmetry classes which are piezoelectric.

A material which undergoes a change in its refractive index in the presence of an electric field can be used in a retardation type of electro-optic modulator. Modulator operation is based on a relative phase retardation which occurs between two polarized components of an incident linearly polarized beam. In the Pockels effect the incident beam polarization axis along which retardation occurs is perpendicular to the applied electric field, whereas in the Kerr effect the axis and the electric field are parallel. The two components of the incident beam polarized along the appropriate electro-optic axes of the material see different refractive indices and therefore travel at different velocities in the material. The relative phase retardation Γ between these components as they emerge from the material is given by

$$\Gamma = \frac{2\pi \ell}{\lambda} \Delta n \ ,$$

where Γ is expressed in radians, λ is the wavelength of the light in vacuum, ℓ is the optical path length of the light in the material, and Δn is the induced birefringence or the difference between the refractive indices for the two components of the light beam.

A time varying electric field applied to an electro-optic material results in a time variation of the induced birefringence Δn. Variations in Γ resulting from electro-optic changes in Δn give rise to phase modulation of the incident beam. If the emerging beam is passed through a linear polarizer whose preferred direction is perpendicular to that of the incident beam polarization, some of the emerging beam will

16

be transmitted. Its intensity I, relative to the incident intensity I_o, is given by

$$I = I_o \sin^2\left(\frac{\Gamma}{2}\right) ,$$

assuming no losses in the material. Variations in Γ resulting from the electro-optic effect thus give rise to intensity modulation of the incident beam. Typical curves showing the transmission of light through the material as a function of modulation voltage are shown in Figure 8 for the linear Pockels effect and the quadratic Kerr effect.
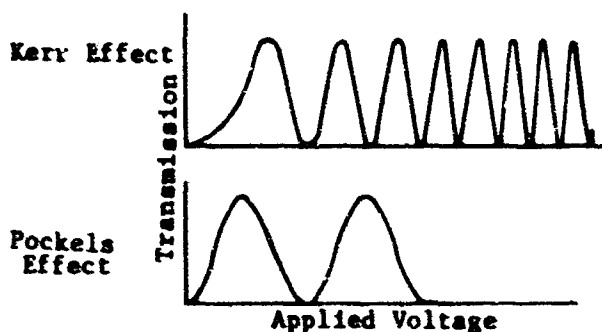

Fig. 8. Comparison of Kerr and Pockels effects.

In the case of the Kerr effect, tne induced birefringence is found to be proportional to the square of the electric field:

$$\Delta n = B\lambda E^2 ,$$

where B is the Kerr constant, λ is the wavelength of light in vacuum, and E is the electric field intensity. B is usually positive, but occasionally is negative (e.g., chloroform). A Kerr cell is an electro-optic modulator using a material with a large Kerr constant such as nitrobenzene.

In order to describe the Pockels effect in detail, it is necessary to consider the change of the orientation and the dimensions of the index ellipsoid under the influence of an electric field. The general equation of the index ellipsoid under

17

the influence of an electric field is given by

$$\left(\frac{1}{n^2}\right)_1 x^2 + \left(\frac{1}{n^2}\right)_2 y^2 + \left(\frac{1}{n^2}\right)_3 z^2 + 2\left(\frac{1}{n^2}\right)_4 yz + 2\left(\frac{1}{n^2}\right)_5 xz + 2\left(\frac{1}{n^2}\right)_6 xy = 1,$$

and

$$\left(\frac{1}{n^2}\right)_i - \left(\frac{1}{n_o^2}\right)_i = r_{ij} E_j ,$$

where
$i = 1$ to 6

$j = 1$ to 3

$r_{ij} =$ linear electro-optic coefficients

$n_o =$ refractive indices in zero field.

The coefficients $(1/n^2)_i$, being reciprocals of the principal dielectric constants, are known as the relative dielectric <u>impermeability coefficients</u>.

It is instructive to apply the above discussion and definitions to uniaxial crystals of the type XH_2PO_4 (e.g., potassium dihydrogen phosphate (KDP) KH_2PO_4) commonly used as linear electro-optic modulators. These crystals have V_d (or $\bar{4}2m$) symmetry. From symmetry arguments, it can be shown that for these crystals r_{41} and r_{63} are the only non-zero electro-optic coefficients ($r_{41} = r_{52}$):

$$r_{ij} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ r_{41} & 0 & 0 \\ 0 & r_{41} & 0 \\ 0 & 0 & r_{63} \end{vmatrix} .$$

ELECTRO-OPTIC EFFECT

Thus, the equation of index ellipsoid under the influence of an electric field becomes

$$\frac{x^2 + y^2}{n_o^2} + \frac{z^2}{n_e^2} + 2r_{63}E_z xy + 2r_{41}(E_x yz + E_y xz) = 1 \ ,$$

where the xyz coordinates are taken as the standard crystallographic axes and n_o and n_e are the ordinary and extraordinary refractive indices in the absence of an electric field. The electro-optic coefficient r_{63} thus describes the effect of a field parallel to the optic axis and the coefficient r_{41} the effect of a field perpendicular to this axis.

The directions of the new optical axes and new principal refractive indices can be determined by rotating the original axes to coincide with those of the deformed index ellipsoid. That is, the index ellipsoid can be rewritten as follows:

$$\left(\frac{x'}{n_{x'}}\right)^2 + \left(\frac{y'}{n_{y'}}\right)^2 + \left(\frac{z'}{n_{z'}}\right)^2 = 1 \ ,$$

where x'y'z' are the new coordinate axes (electro-optic axes) and $n_{x'}$, $n_{y'}$, and $n_{z'}$ are the new refractive indices. For an electric field in the z-direction ($E_z = E$; $E_x = E_y = 0$), it can be shown that this transformation of coordinates yields the results

$$n_{x'} = n_o + \tfrac{1}{2} n_o^3 r_{63}E$$
$$n_{y'} = n_o - \tfrac{1}{2} n_o^3 r_{63}E$$
$$n_{z'} = n_e$$

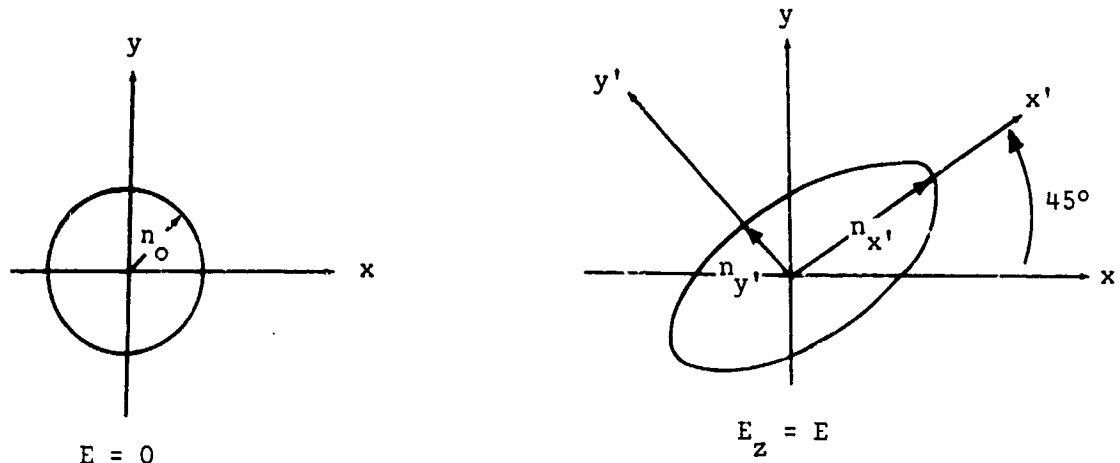where the z' axis coincides with z, while x' and y' are rotated by 45 degrees from x and y (Figure 9).

Fig. 9. Ellipse formed by the z = 0 plane and the index ellipsoid in a crystal of $\bar{4}2m$ symmetry with $E = E_z$.

A beam of linearly polarized light propagating parallel to the electric field and the optic axis of the crystal, and with its plane of polarization parallel to either the x or y axis, will emerge from the crystal exhibiting a relative phase shift between the fast and slow components of

$$\Gamma = \frac{2\pi\ell}{\lambda} \Delta n = \frac{2\pi\ell}{\lambda} (n_{x'} - n_{y'}) = \frac{2\pi n_o^3 r_{63} V}{\lambda} \quad,$$

where $V = E \cdot \ell$ is the voltage applied to the crystal. Notice that, in this particular example, the induced phase shift is independent of the path length and depends only on the applied voltage.

The voltage required to produce a phase shift of half a wave ($\Gamma = \pi$) is known as the half-wave voltage. In the above example

$$V_{\frac{1}{2}} = \frac{\lambda}{2n_o^3 r_{63}}.$$

Since crystals that exhibit the electro-optic effect are also piezoelectric, different values will be obtained for the electro-optic coefficients depending on whether the crystal is in a condition of constant stress (free) or constant strain

20

(clamped). The equation relating the linear coefficients for constant stress (<u>unclamped electro-optic coefficients</u>) r_{ij} to the coefficients for constant strain (<u>clamped electro-optic coefficients</u>) r_{ij}' can be written

$$r_{ij} = r_{ij}' + \sum_{k=1}^{6} p_{ik} d_{jk} \quad,$$

where p_{ik} are the elasto-optic coefficients and d_{jk} are the piezoelectric coefficients. Here, r_{ij}' are the electro-optic coefficients associated with the direct or primary effect of the electric field on the atomic polarizability or the refractive index, while r_{ij} are the electro-optic coefficients which represent the total effect of the electric field on the constants of the index ellipsoid; the difference between the two is a secondary effect due to piezoelectric deformation. If the driving electric fields are at a frequency corresponding to an acoustic resonance of the crystal, the secondary effect may be as large as the direct effect. At sufficiently high frequencies, however, the crystal strain cannot follow the field and only the direct effect is important ($r_{ij} = r_{ij}'$).

FARADAY EFFECT

The Faraday effect is observed when plane polarized light is passed through a transparent isotropic material which is held in an external static magnetic field. The plane of polarization of the light is rotated as a result of the magnetic field, and the amount of magneto-optic rotation θ is given by the equation

$$\theta = V \, H \, \ell \cos \delta \; ,$$

where V is the Verdet constant of the material, H is the strength of the magnetic field, ℓ is the length of the light path through the material, and δ is the angle between the direction of the magnetic field and the direction of the light beam. V is positive if the direction of rotation is the same as the direction of the electric current which produces the magnetic field. The rotation results because the magnetic field affects the velocity of the right circularly polarized component of the light beam differently than it does the velocity of the left circularly polarized component and therefore the refractive indices of the two components, n_R and n_L, are different. The Verdet constant of a material is given by the formula

$$V = \frac{\pi}{\lambda} (n_R - n_L) \; ,$$

where λ is the wavelength of the incident light beam. Typical units for the Verdet constant are degrees per oersted per centimeter.

In magneto-optic experiments, the term Faraday configuration is used to describe incident radiation propagating parallel ($\delta=0$) to the externally applied magnetic field.

The Faraday effect can also be observed when plane polarized light is passed along the optic axis of uniaxial doubly refracting crystals; the effect is masked by birefringence in other directions.

23

FARADAY EFFECT

In the case of ferromagnetic materials, the Verdet constant is often proportional to the susceptibility. Therefore, the Kundt constant, which is equal to the Verdet constant divided by the susceptibility, is measured.

In the case of semiconductors, the Faraday effect can be considered to consist of two additive components. The first, called the interband Faraday effect, is due to differences in probability for the various virtual transitions of valence electrons from the Zeeman split Landau levels of the valence band to those of the conduction band. This first component is large for a photon of energy corresponding to the band-gap energy and it decreases as the energy decreases. The second component, called the free-carrier Faraday effect, is due to virtual transitions of conduction electrons to the Zeeman split Landau levels of the conduction band. In the infrared region, where the light frequency is large compared to the cyclotron resonance and collision frequencies, the Verdet constant for the free-carrier Faraday rotation is given by

$$V_{FC} = \left(\frac{e^3}{3\pi^2 \, c^3 \, \epsilon_o}\right) \left(\frac{N\lambda^2}{m^{*2} \, n}\right)$$

where N is the free-carrier concentration, λ is the wavelength of the light beam, m^* is the effective mass, n is the refractive index, e is the charge of an electron, c is the velocity of light in vacuum, and ϵ_o is the permittivity of free space. By measuring the Faraday rotation in the infrared region and correcting for the small contribution of the interband Faraday effect, the effective carrier mass can be calculated.

The inverse Faraday effect has also been observed. In this case circularly polarized light, passing through a non-absorbing material, induces a magnetization which is proportional to the Verdet constant of the material.

KERR MAGNETO-OPTIC EFFECT

If a beam of plane polarized light is reflected from the surface of a magnetized ferromagnetic material, the reflected beam becomes slightly elliptically polarized with the major axis of the ellipse rotated through a small angle from the plane of the incident electric vector. This is known as the Kerr magneto-optic effect. It has been attributed to the spin-orbit interaction of the electrons in the ferromagnetic material with the magnetic field inside the material. The resultant differing effects on right- and left-circularly polarized components of the incident beam of light produce an elliptically polarized reflected beam.

There are three types of Kerr magneto-optic effects, depending on the relation between the magnetization of the reflecting material and the plane of incidence of the light beam. In the polar effect, the magnetization is perpendicular to the reflecting surface. The phenomenon is called the ferromagnetic Faraday effect when considering the transmitted beam. In the longitudinal effect, the magnetization is parallel to the reflecting surface and to the plane of incidence. In the transverse effect, the magnetization is parallel to the reflecting surface and perpendicular to the plane of incidence.

The Kerr magneto-optic effect is proportional to the magnetization of the material and not to the external magnetic field. Temperature has an effect only through its influence on the intensity of magnetization, except that the Kerr magneto-optic effect disappears above the Curie temperature where the material is no longer ferro-magnetic.

The Kerr magneto-optic effect has been used to study the surface domain structure of ferromagnetic materials and to determine the state of magnetization of ferromagnetic films.

LASER PROPERTIES

The word laser is an acronym derived from "light amplification by stimulated emission of radiation." The term optical maser is often used to describe the same phenomenon. A laser produces a narrow beam of coherent electromagnetic radiation having a particular well-defined frequency in the region of the spectrum including the near ultraviolet, the visible, and the infrared.

The term coherence is defined as the correlation observed at the same point in space between the phases of monochromatic radiation emanating from two different points. Ordinary sources of radiation in the optical region, such as incandescent and fluorescent lamps, are incoherent. Spatial coherence is the correlation between the phases of two electromagnetic fields observed at different points in space. The degree of coherence is related to the characteristics of the source. Consider a source of radiation producing an electromagnetic field which varies sinusoidally for a certain time τ and then changes phase abruptly; τ is defined as the coherence time. The coherence length L is given by

$$L = c\tau = c/\Delta\nu \quad ,$$

where $\Delta\nu$ is the line width of the source and c is the velocity of light. Using the fact that $\Delta\nu/\nu = \Delta\lambda/\lambda$, the coherence length can be expressed in terms of the source wavelength λ by

$$L = \lambda^2/\Delta\lambda \quad ,$$

where $\Delta\lambda$ is the line width of the source on the wavelength scale.

Coherence of the light emerging from a laser and the sharp directionality of the laser beam are closely related phenomenon. Assuming radiation from a circular aperture of diameter d radiating in phase and with uniform amplitude, the angular spread or

27

LASER PROPERTIES

beamwidth of a laser is given by

$$\theta = 1.22 \ \lambda/d \quad,$$

where λ is the laser wavelength. In practice, much larger beamwidths are observed. This is probably due to the fact that the entire surface area of the laser does not participate in radiation in the manner assumed by the above diffraction theory.

Two conditions must be fulfilled in order to bring about laser action (self-sustained oscillation): (1) population inversion must be achieved between the two electronic levels involved in a fluorescent transition and (2) an avalanche process of photon amplification, sufficient to overcome losses, must be established in an optical cavity.

The most effective method of obtaining population inversion in a fluorescent solid is to use a sufficiently intense light source to induce an absorption transition at a wavelength shorter than the laser output transition. This is known as optical pumping.

The terms three level laser and four level laser describe the two useful energy level schemes which characterize fluorescent solids exhibiting laser action. The original ruby laser is an example of a three level laser. A typical energy level diagram is shown in Figure 10.

A characteristic of a three level system is that the terminal level for laser emission is the lowest (ground) state of the system. In thermal equilibrium, essentially all of the laser ions are in this ground state. Absorption (optical pumping) raises ions from the ground state to the broad band of energy states (pump band) at level 3. These excited ions will drop to the ground state in two steps. In the first drop from the pump band to level 2, the ions make a radiationless transition in which they give up some of their energy to the crystal lattice and no light is emitted. This transition takes place with a non-radiative transition rate S_{32}. The second

drop from level 2 to the ground state is accompanied by emission of energy in the form
of photons. This transition can either be a spontaneous emission (ordinary fluores-
cence), occurring with a spontaneous emission rate A_{21}, or the laser transition,
occurring with a __stimulated emission rate__ of W_{21}. To achieve population inversion in
three level pulsed lasers, more than half the ions must be pumped from the ground
state to level 2 via level 3. With sufficiently intense continuous pumping, since
level 2 is a __metastable state__ (long lifetime), the ion population will accumulate
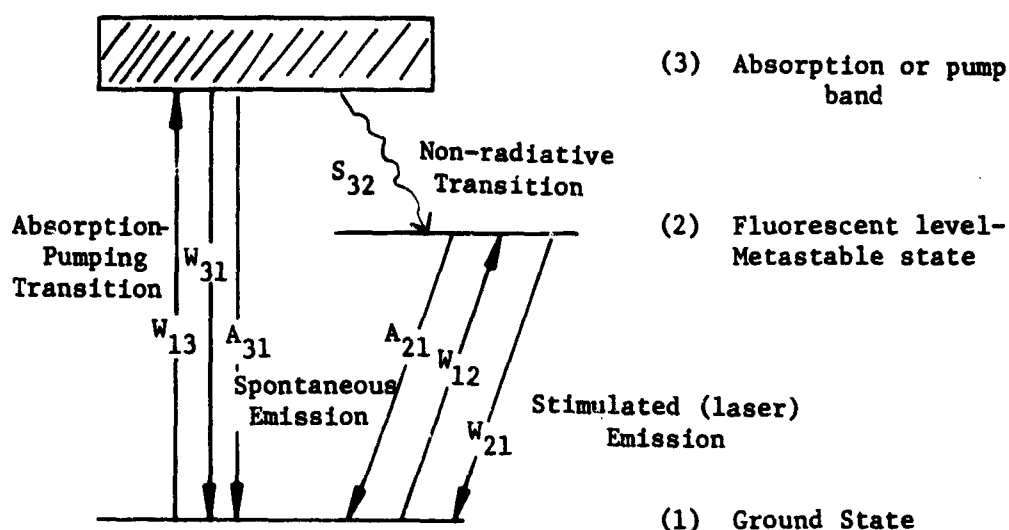there, resulting in population inversion over the ground state.

Fig. 10. Energy level diagram for a three level laser.

In order to estimate the pump power to obtain population inversion ($N_2 \geqslant N_1$),
the kinetics of pumping and fluorescence must be considered. The occupation of levels
in a three level system with a total of N_o atoms per unit volume is governed by the
__rate equations__

$$dN_3/dt = W_{13}N_1 - (W_{31} + A_{31} + S_{32})N_3 ,$$

$$dN_2/dt = W_{12}N_1 - (W_{21} + A_{21})N_2 + S_{32}N_3 ,$$

$$N_o = N_1 + N_2 + N_3.$$

29

LASER PROPERTIES

Under the following assumptions

(1) Steady state conditions; $\frac{dN_3}{dt} = \frac{dN_2}{dt} = 0$

(2) A_{31} low compared to all other processes

(3) Non-degenerate energy levels; $W_{13} = W_{31}$; $W_{21} = W_{12}$

(4) High fluorescent quantum efficiency; $S_{32} \gg W_{13}$; $\tau_{21} = \frac{1}{A_{21}}$

the steady state solution of the rate equations simplifies to

$$\frac{N_2 - N_1}{N_o} = \frac{W_{13} - A_{21}}{W_{13} + A_{21} + 2W_{12}} .$$

Therefore, in order to obtain population inversion such that $N_2 > N_1$, we must have $W_{13} > A_{21}$ as a minimum condition.

A typical energy level diagram for a four level laser is shown in Figure 11. In this case the ions are again optically pumped from the ground state to the fluorescent level via the pump band. Since the fraction of the ions in level 2 is small, the number which must be raised from the ground state to level 3 does not have to be large for a population inversion to exist between levels 2 and 3. Hence the four level laser requires lower threshold pumping energies than the three level laser.

Once population inversion is achieved, amplification of the fluorescence radiation will occur through stimulated emission. By placing the laser material between highly reflecting, plane-parallel mirrors, regeneration of the optical radiation is effected. The optical cavity is called a Fabry-Perot interferometer or etalon, respectively, depending on whether the mirror spacing can be mechanically varied or is held fixed.

For self-sustained oscillation, the gain obtainable from the excess population $(N_2 - N_1)$ must be sufficient to overcome the circuit losses in a cavity. The laser oscillation threshold can be defined as that point at which the material gain equals
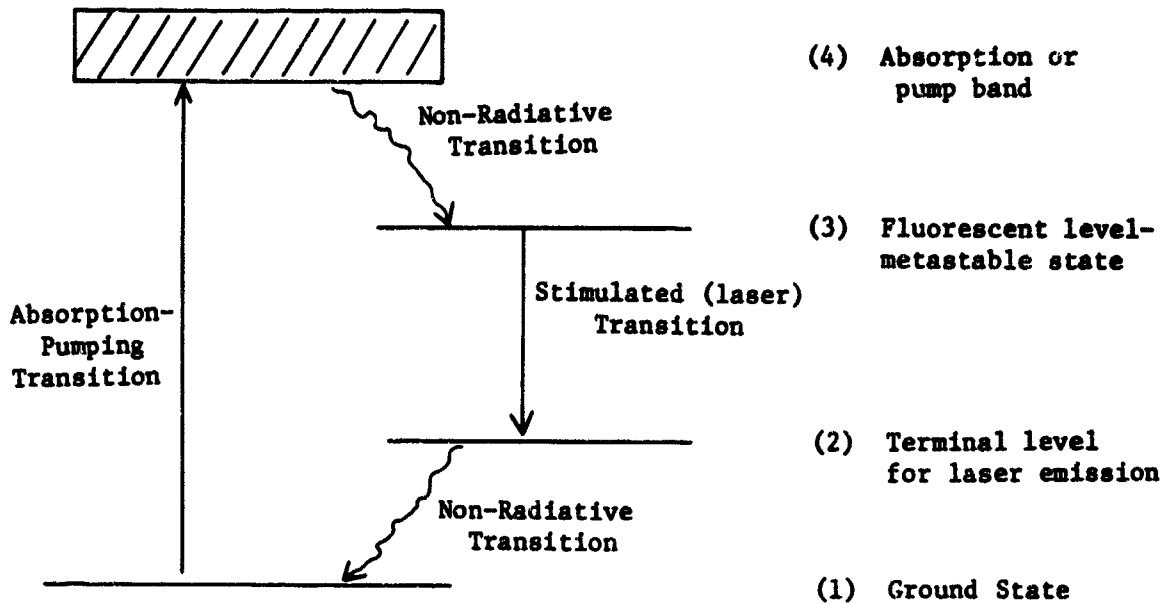
30

Fig. 11. Energy level diagram for a four level laser.

(or exceeds) the circuit losses. For the laser configuration shown in Figure 12, this statement can be expressed as

$$e^{-2\alpha(\nu_o)\ell} \geq 1/R^2 \quad ,$$

where R is the reflectivity of the end mirrors, ℓ is the length of the laser material, and $\alpha(\nu_o)$ is the absorption coefficient at the center ($\nu = \nu_o$) of the fluorescent line. If the reflectivities of the two mirrors are different, R is replaced by its geometric mean, $\sqrt{R_1 R_2}$. Equivalently (see Absorption),

$$-\alpha(\nu_o)\ell = (N_2 - N_1) \sigma (\nu_o)\ell \geq \text{Log}_e (1/R) \quad ,$$

where $\sigma(\nu_o)$ is the transition cross section at the center of the line [for (1-R)<<1, $\text{Log}_e(1/R) \approx 1-R$]. Thus the population inversion $\Delta N = N_2 - N_1$ which must be developed by the pumping system to overcome circuit losses is given by

$$\Delta N = N_2 - N_1 = \frac{1-R}{\sigma(\nu_o)\ell} \quad .$$
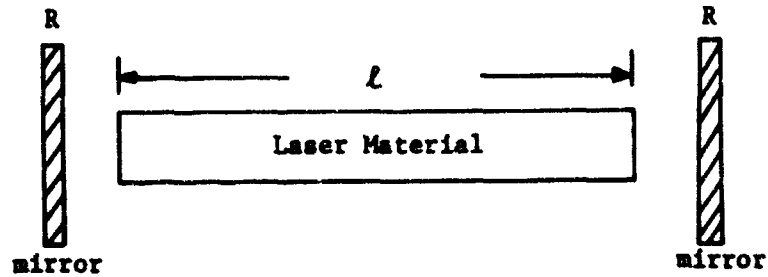
31

Fig. 12. Optical cavity

The circuit losses are often expressed in terms of a <u>cavity decay time</u> τ_c:

$$\tau_c = \frac{\ell n}{c(1-R)} \, ,$$

where n is the refractive index of the laser material and c is the velocity of light in vacuum. This decay time is related to the cavity <u>quality factor</u> Q by

$$Q = 2\pi\nu\tau_c .$$

The quality factor is defined as the energy stored in the cavity divided by the energy loss per radian of oscillation.

The transition cross section can be expressed as

$$\sigma(\nu_o) = \frac{c^2}{8\pi\nu^2 n^2 \tau_{21}} f(\nu_o) \, ,$$

where τ_{21} is the natural lifetime of level 2 and $f(\nu_o)$ is the atomic line shape factor.

LASER PROPERTIES

Using the expressions on the previous page for τ_c and $\sigma(\nu_o)$, we obtain the threshold population in terms of fundamental laser parameters:

$$\Delta N = N_2 - N_1 = \left(\frac{\tau_{21}}{\tau_c}\right) \frac{8\pi\nu^2 n^3}{c^3 f(\nu_o)} .$$

A mode of laser operation extensively employed for the generation of high pulse power is known as Q-spoiling or Q-switching. The quality factor Q of the resonant cavity is kept low during the initial pumping phase such that cavity losses are large enough to inhibit self-sustained oscillation. After considerable energy is stored in the laser material, Q is increased, generally by changing the reflectivity of one of the end mirrors, resulting in a sudden conversion of this energy into a large stimulated photon flux.

In a semiconductor laser (or injection laser diode) the relevant energy levels are those of the electrons in the conduction band and in the valence band on the n- and p-sides, respectively, of a heavily doped p-n junction (Figure 13). For laser action to occur, the junction is heavily biased in the forward direction. The current carriers, electrons and holes, injected across the junction, recombine. The resulting recombination radiation occurs at a frequency ν corresponding to the band gap E_g of the semiconductor:

$$h\nu = E_g .$$

33

Junction Region

p-type   n-type

Electrons

ϕ_f

Electrons

(a)

Junction Region

p-type   n-type

ϕ_c

Electrons

hν   eV E_g
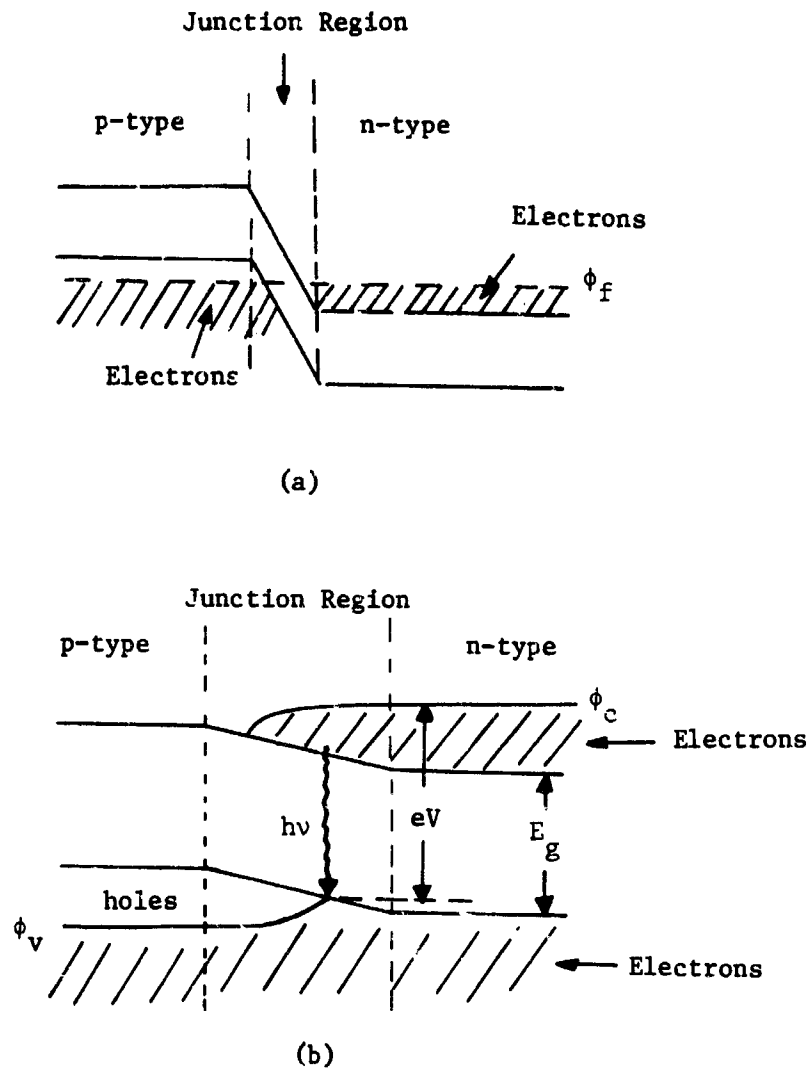
holes

ϕ_v

Electrons

(b)

Fig. 13. Band structure of heavily doped p-n junction suitable for laser diode: (a) Equilibrium band structure (no bias), showing location of Fermi level ϕ_f. (b) Band structure for forward biased junction, showing laser transition hν.

34

LASER PROPERTIES

Population inversion is said to occur in a laser diode when the bias voltage V applied between the p-and n-material displaces the Fermi level on the n-side, ϕ_c, from that on the p-side, ϕ_v, an amount greater than the band gap Eg:

$$\phi_c - \phi_v = eV > E_g = h\nu.$$

The optical cavity which allows amplification of the stimulated emission is formed by the end faces of the laser diode itself. These faces can be polished, but cleaving along the crystalline planes has proved to be successful in obtaining the required flat and parallel surfaces.

The laser output wavelength is given by

$$\lambda = c/\nu = hc/\Delta E \quad ,$$

where ΔE is the energy separation of the levels involved in the stimulated transition. In an optical cavity, however, not all frequencies are permitted to oscillate; only a discrete number of cavity modes are allowed. A mode may be defined as an electric or magnetic field distribution that reproduces itself in spatial distribution and phase as the electromagnetic wave oscillates between two reflectors. The wavelength at each cavity mode is given by

$$\lambda = 2L/m \quad ,$$

where L is the length of the optical cavity, and m is an integer that defines the mode number (Figure 14). For optical wavelengths, m will be a large number ($m = 10^5$). The spacing between modes is given by (Figure 15)
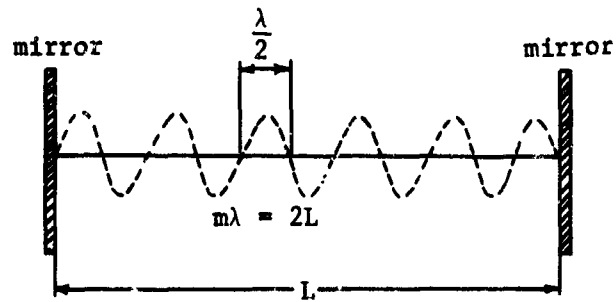
$$\Delta\lambda = \lambda^2/2L.$$
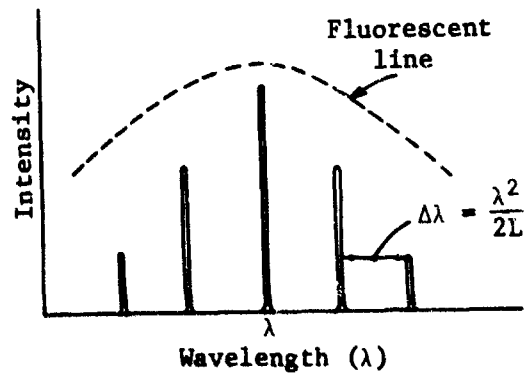
35

Fig. 14. Resonant cavity

Fig. 15. Fluorescent linewidth of laser
transition compared with mode linewidth
and mode spacing in a laser material.

36

NONLINEAR OPTICAL EFFECTS

The polarization P induced by the electric field E of electromagnetic radiation passing through a material is given by the equation

$$P = \kappa E + \chi E^2 + \theta E^3 + \dots \quad .$$

In the case of ordinary light beams, only very weak electric and magnetic fields are generated, and the optical electric field is assumed to be only a small perturbation on the internal atomic fields of the material; hence terms involving powers of E greater than 1 are negligible and the polarization induced by the optical electric field is directly proportional to that field:

$$P = \kappa E.$$

However, at optical electric field intensities of the order of 10^4 to 10^5 V/cm (power densities of $\sim 10^5$ to 10^7 W/cm^2), which are easily obtainable with present day high-powered lasers, this assumption breaks down.

This failure of the simple linear approximation leads to mixing of fields (or parametric interaction) in transparent, nonlinear dielectric media. In the case of two optical fields at angular frequencies ω_1 and ω_2,

$$E = E_1 + E_2$$
$$E_1 = A_1 \sin (\omega_1 t - \vec{k}_1 \cdot \vec{r})$$
$$E_2 = A_2 \sin (\omega_2 t - \vec{k}_2 \cdot \vec{r}) ,$$

where $\vec{k}$ is a propagation vector given by the formula

$$\vec{k} = \frac{2\pi}{\lambda} \hat{k} .$$

Here, λ is the wavelength of the light and $\hat{k}$ is a unit vector in the direction of

propagation of the light. These two optical fields will produce a frequency dependent polarization:

$$P = \kappa (A_1 \sin \omega_1 t + A_2 \sin \omega_2 t)$$
$$+ \chi A_1^2 \sin^2 \omega_1 t + \chi A_2^2 \sin^2 \omega_2 t$$
$$+ 2 \chi A_1 A_2 \sin \omega_1 t \sin \omega_2 t .$$

This can be simplified to

$$P = \kappa (A_1 \sin \omega_1 t + A_2 \sin \omega_2 t)$$
$$+ \chi \frac{(E_1^2 + E_2^2)}{2} + \frac{\chi}{2} (E_1^2 \cos 2\omega_1 t + E_2^2 \cos 2\omega_2 t)$$
$$+ \chi E_1 E_2 [\cos (\omega_1 - \omega_2)t + \cos (\omega_1 + \omega_2)t].$$

It can be seen that the presence of the nonlinear term in the relationship between P and E generates second harmonics, both sum and difference frequency terms, and a constant polarization term. The process by which a harmonic light beam, with a frequency twice that of the fundamental, is formed is called second harmonic generation (SHG). The new beams which are formed have $\vec{k}$ values which depend on the $\vec{k}$ values of the original beams:

$$\vec{k} = 2\vec{k}_1 \qquad \text{(second harmonic generation, } \omega = 2\omega_1)$$
$$\vec{k} = \vec{k}_1 + \vec{k}_2 \quad \text{(sum of frequencies beam, } \omega = \omega_1 + \omega_2)$$
$$\vec{k} = \vec{k}_1 - \vec{k}_2 \quad \text{(difference of frequencies beam, } \omega = \omega_1 - \omega_2)$$

Optical rectification, characterized by the constant polarization term, is a nonlinear effect related to second harmonic generation, in that they occur simultaneously when a high-power laser beam passes through a material. This steady polarization (or direct current polarization) is a component of the total non-linear polarization

38

produced by the laser beam in the material. It is determined by measuring the voltage developed across the material during the passage of the laser beam.

The simple scalar relationship between P and E, described above, is not typical for dielectric crystals. Instead, the following tensor relationship can be written for the second-order polarization:

$$P_i = d_{ij}(E^2)_j ,$$

where

$$i = 1 \text{ to } 3$$

$$j = 1 \text{ to } 6$$

$$d = \underline{\text{second-order polarization tensor}}$$

$$
\begin{vmatrix} P_x \\ P_y \\ P_z \end{vmatrix}
=
\begin{vmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{vmatrix}
\begin{vmatrix} E_x^2 \\ E_y^2 \\ E_z^2 \\ 2E_y E_z \\ 2E_x E_z \\ 2E_x E_y \end{vmatrix}
$$

Symmetry relations for second harmonic generation are the same as for piezoelectric effects. Crystals that possess a center of symmetry (d_{ij}=0) cannot exhibit bulk second harmonic generation; if P is an odd function of E, frequency doubling is not possible. The materials must of course be transparent to the fundamental optical frequency and to its second harmonic, yet harmonic generation can occur on reflection from piezoelectric crystals that are opaque at these two frequencies (tellurium, for example). Second harmonics can also be produced at the surfaces of crystals with a center of symmetry.

NONLINEAR OPTICAL EFFECTS

When a second harmonic light beam is generated, it will interfere with the funda-
mental laser light beam; since the refractive index of the material in which the
generation takes place will generally be different for light of the two frequencies,
this interference is destructive. The distance in which the fundamental and the
second harmonic light beams become 180° out of phase is called the coherence distance;
it is determined by the dispersion of the nonlinear material, and is usually of the
order of 10 microns. Therefore, unless the interference is prevented, crystals used
for second harmonic generation must be very thin. Furthermore, when it is desired to
convert light beams of two different frequencies into beams containing the sum or the
difference of these frequencies, destructive interference between these various light
beams must be eliminated. This is more difficult than in the case of second harmonic
generation as three, rather than two, beams are involved. One technique for making
the interference constructive is called index matching. In certain optically aniso-
tropic crystals, such as potassium dihydrogen phosphate, it is possible to find a
direction of propagation (synchronism direction) in which the refractive indices at
the different frequencies for orthogonal polarizations (ordinary and extraordinary
rays) are equal, or almost equal:

$$n_o(\omega_1) \approx n_e(\omega_2).$$

This direction will vary depending on the frequencies which must be accommodated. The
interference is now constructive, and the efficiency of generation is orders of magni-
tude larger. The angle between the synchronism direction and the optic axis is called
the index matching angle.

Another non-linear optical phenomenon is parametric amplification. The energy
of a high intensity light beam (called the pump beam, with frequency ω_p) is converted
in a crystal to less energetic beams at frequencies ω_1 and ω_2 such that

$$\omega_p = \omega_1 + \omega_2 \; ,$$

and
$$\vec{k}_p = \vec{k}_1 + \vec{k}_2 \; .$$

The frequencies ω_1 and ω_2 are determined by tuning the crystal by various methods, including adjusting the angle at which index matching occurs and varying the crystal temperature. When the crystal is used for parametric amplification, a signal beam of frequency ω_s is passed into the properly tuned crystal along with the pump beam $(\omega_p > \omega_s)$ and part of the pump beam is converted, through interaction with the signal beam, to the same frequency as the signal beam; part is converted to an _idler beam_ of frequency ω_i, such that

$$\omega_p = \omega_s + \omega_i \; .$$

The signal beam is thus amplified. After interaction between the signal beam and the pump beam for a distance ℓ in the crystal, the electric field of the resulting amplified signal beam is given by

$$E_s(\ell) = E_s(o) \, e^{\Gamma_o \ell} \; .$$

$E_s(o)$ is the electric field of the input signal beam and Γ_o, the _parametric gain_, is given by

$$\Gamma_o = \frac{\pi}{2} \frac{\chi(E_p)}{\epsilon_o} \; ,$$

where ϵ_o is the static dielectric constant of the material. If the parametric gain exceeds the optical circuit losses in a suitable optical cavity, the system will oscillate. Such parametric oscillators have been used to convert the discrete output of high powered lasers, and may serve as continuously tunable coherent optical sources.

PHOTOELASTIC EFFECT

If a transparent isotropic material is subjected to mechanical stress, it may become optically anisotropic and exhibit birefringence. This phenomenon is called the photoelastic effect or stress birefringence. The amount of induced birefringence is proportional to the stress and also depends on the direction of application of the stress.

The photoelastic behavior of a crystal may be analyzed by means of strains or stresses in terms of its set of elasto-optic coefficients, p_{ij}, or its set of piezo-optic coefficients, q_{ij}, respectively. These are sometimes called the strain-optic and stress-optic coefficients, respectively. Together, these make up the photoelastic coefficients of the crystal. The coefficients p_{ij} and q_{ij} are related as follows:

$$p_{ij} = \sum_{k=1}^{6} q_{ik} c_{kj} , \qquad q_{ij} = \sum_{k=1}^{6} p_{ik} s_{kj} , \qquad (i,j = 1 \text{ to } 6) ,$$

where c_{jk} and s_{jk} are the elastic constants (or elastic stiffness) and the elastic moduli (or compliance coefficients), respectively. The elasto-optic coefficients p_{ij} are dimensionless; the piezo-optic coefficients q_{ij} are expressed in units of $cm^2/dyne$.

Because of the symmetry properties of crystals, the number of independent coefficients in each set is usually much less than the 36 constants of the general case. The 32 crystal classes can be divided into 11 photoelastic groupings with the number of coefficients varying from 3 to 35 in each set. Isotropic solids have 2 elasto-optic coefficients, p_{11} and p_{12}, and 2 piezo-optic constants, q_{11} and q_{12}.

The photoelastic constants of a crystal can be evaluated by observing the absolute and relative retardations induced by stress in suitably oriented specimens. The retardations are a result of the change of refractive index and of the thickness of the specimen.

43

PHOTOELASTIC EFFECT

If the thickness is determined, the constants can be calculated from the observed retardation. When isotropic materials are used for stress analysis, a single constant C, the **engineering stress-optical coefficient**, is used in place of q_{11} and q_{12}. The phase retardation Γ in fractions of a wave, is given by the equation

$$\Gamma = \frac{n^3}{2\lambda} (q_{11} - q_{12}) \, T \, \ell = C \, \frac{T\ell}{\lambda} \, ,$$

where n is the ordinary refractive index, λ is the wavelength in angstroms, T is the stress in bars (1 bar = 10^6 dyne/cm^2), ℓ is the light path in millimeters, and C is in brewsters (1 brewster = 10^{-13} cm^2/dyne).

The photoelastic effect is the basis of an optical method of stress analysis in structures, in which models are prepared from transparent materials and are observed between two crossed polarizers while stress is applied. Since the induced birefringence is proportional to the stress, points of equal stress have the same appearance. The direction of the principal stresses at a point is determined by rotating the crossed polarizers until a black band (isoclinic line) passes through the point, since the isoclinic lines contain the points where the stress axis is parallel to the light direction transmitted by either of the two crossed polarizers.

PHOTON EMISSIVITY

A blackbody is defined as a body which absorbs all and reflects none of the radiation which falls on it. At the same time, such a blackbody is the best emitter of radiation, and gives off energy at the maximum possible rate per unit area at all wavelengths at any temperature. A blackbody emits energy at a rate given by the Stefan-Boltzmann law:

$$W = \sigma T^4 \quad ,$$

where W is the radiant emittance or rate of energy emission per unit area of source in all radial directions, σ is the Boltzmann constant, and T is the absolute temperature. The emittance ϵ of a non-blackbody is the ratio of its radiant emittance (W') to the blackbody radiant emittance at that temperature

$$W' = \epsilon W = \epsilon \sigma T^4$$

The emittance of a non-blackbody can be described and measured in various ways. Thus, emittance itself is a ratio involving the rate of energy emission per unit area of source. Hemispherical emittance is an analogous ratio involving the rate of energy emission from the entire area of the source. Spectral emittance is a similar ratio involving the rate of energy emission per unit area of source per unit wavelength interval, while total emittance is a ratio involving the rate of energy emission per unit area of source over the whole spectrum. The rate of energy emission per unit solid angle per unit projected area is the radiance (sometimes called the steradiancy) of a body, and the ratio of a body's radiance to that of a blackbody under the same conditions is the directional emittance of that body. When the emission is in a direction normal to the surface, the directional emittance becomes the normal emittance. Various combinations are possible, such as hemispherical

45

PHOTON EMISSIVITY

tot. ' emittance or normal spectral emittance.

Lambert's cosine emission law states that the radiant power per unit solid angle emitted in any direction from a plane source of radiation varies as the cosine of the angle between the normal to the surface and the direction. Since the apparent (or projected) area of the radiation source varies in the same way with the cosine of this angle, the radiance of a surface which obeys the law is constant regardless of the direction. For most metals the radiance first increases as the angle increases from 0°, but then decreases rapidly to zero as the angle nears 90°. The radiance of other materials, such as metal oxides and carbon varies in just the reverse manner.

The emissivity of a material is the emittance of that material in the form of a body with an optically smooth surface and of sufficient thickness to be opaque. It is an intrinsic property of the material. The emittance of a body of the material will approach the emissivity of the material as the optical smoothness of the surface is improved. The spectral emissivity of a non-blackbody is its emissivity at a specific wavelength or wavelength interval.

The distribution of the energy emission of a blackbody over the spectrum at a particular temperature is given by Planck's distribution law, which can be approximated (within 1 percent when λT is less than 0.3 cm-°K) by Wien's distribution law:

$$W_\lambda = C_1 \lambda^{-5} e^{-\frac{C_2}{\lambda T}}$$

where W_λ is the spectral radiant emittance at a particular wavelength λ, and C_1 and C_2 are the first and second radiation constants. Wien's displacement law states that

PHOTON EMISSIVITY

for blackbody, the product of its temperature and the wavelength (λ_{max}) of maximum spectral radiant emittance (W_{max}) is constant

$$\lambda_{max} T = 0.2898 \text{ cm-deg}$$

and also

$$W_{max} T^{-5} = 1.285 \times 10^{-11} \text{ watt-cm}^{-3}\text{-deg}^{-5}.$$

A graph showing the distribution of energy emission by a blackbody is given in Figure 16.
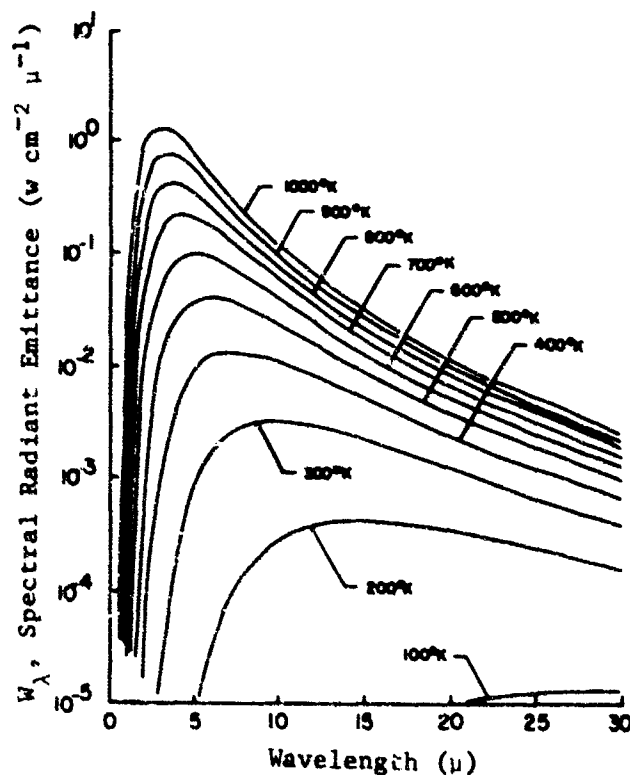

Fig. 16. Blackbody curves, 100°K to 1000°K.

PHOTON EMISSIVITY

According to <u>Kirchhoff's radiation law</u>, the ratio of the radiant power to the absorptivity of a material depends only on the wavelength of the radiation and the temperature, and is equal to the radiant power of a blackbody at the same temperature and wavelength. The absorptivity of a blackbody is unity by definition.

Emission of light which is not due to thermal excitation is indexed under Photon Luminescence.

PHOTON LUMINESCENCE

Luminescence is the emission of light from a material due to the decay of a
metastable excited electronic state. It includes all light emission phenomena with
the exception of those de-excitation processes leading to blackbody radiation. Mate-
rials which exhibit luminescence are called phosphors. Luminescence is arbitrarily
divided into the categories fluorescence and phosphorescence according to whether the
lifetime of the decay process is short or long. Decay time for fluorescence is
temperature independent, while decay time for phosphorescence is temperature dependent.

The nature of the excitation mechanism is frequently specified by the addition
of a prefix. Some examples are triboluminescence (mechanical luminescence), thermo-
luminescence, electroluminescence, photoluminescence, chemiluminescence, biolumines-
cence, and roentgenoluminescence.[*] Many of the non-metallic materials exhibit lumin-
escence due to diverse mechanisms. It seems to be a condition for luminescence that
some activator atoms be present in small concentrations in the host lattice. Impurities
which are thought to inhibit the luminescent activity of other luminescent centers
are called killer atoms or poisons. If there are too many activator atoms in a cer-
tain volume of material, they have an inhibiting effect on each other known as quench-
ing.

The energy of the emitted photons is equal to or less than that of the exciting
photons (Stokes' law) because part of the energy of de-excitation is almost always
dissipated by lattice vibration or phonon emission. The shift in energy is called
the Stokes shift. Stokes' law does not apply in a few cases where thermal energy
contributes slightly to the input excitation energy and where laser irradiation pro-
duces nonlinear optical effects.

[*]All of these terms, except the first three (which are separately indexed), are indexed
under Photon Luminescence.

PHOTON LUMINESCENCE

Luminescence has been widely used to study energy levels, and has found important applications in radiation detectors, fluorescent lights, cathode ray tubes, and solid state lasers.

The quantum efficiency, η, of a phosphor is the number of fluorescent photons emitted by the sample per photon absorbed:

$$\text{quantum efficiency} = \eta = \frac{\text{no. of photons emitted by sample}}{\text{no. of photons absorbed by sample}}$$

A similar term, the quantum yield, is defined as follows:

$$\text{quantum yield} = \phi = \frac{\text{no. of photons falling on sample}}{\text{no. of photons emitted by sample}}$$

These two are related by the equation

$$\eta = \frac{1}{\phi} \cdot \frac{1}{1-R} \ ,$$

where R is the reflection coefficient for the exciting light.

The fluorescent quantum efficiency is given by

$$\eta_f = \frac{\tau_i}{\tau_{ij}} \ ,$$

where τ_i is the luminescence lifetime (or fluorescence lifetime) of the excited state i and τ_{ij} is the natural lifetime of the excited state i for spontaneous emission to state j. The natural lifetime τ_{ij} is also referred to as the radiative or spontaneous emission lifetime.

The luminescence lifetime of an excited state i is the time constant for relaxation of that excited state. The lifetime, τ_i, is determined by the natural lifetime for spontaneous emission, τ_{ij}, and the radiationless transition rate, ω_{ik}, in the following manner:

$$\frac{1}{\tau_i} = \sum_j \frac{1}{\tau_{ij}} - \sum_k \omega_{ik}.$$

PHOTON LUMINESCENCE

The radiative decay depends on the number of excited atoms, N_i, and the natural life-time, and can be described by a differential equation of the form

$$\frac{dN_i}{dt} = -N_i \left(\frac{1}{\tau_{ij}}\right) = -N_i A_{ij} \; ,$$

where A_{ij} is the __spontaneous emission rate__ (and is the reciprocal of the lifetime). Solving this equation gives

$$N_i = (N_i)_0 \; e^{-t/\tau_{ij}} = (N_i)_0 \; e^{-A_{ij}t} \; ,$$

where $(N_i)_0$ is the value of N_i at $t = 0$. During the time τ_{ij} the number of excited atoms decreases by a factor e.

In practice, the luminescence lifetime τ_i can be measured directly by observing decay of fluorescence while the natural lifetime τ_{ij} can be calculated from the characteristics of the fluorescent (or absorption) line shape. For a Lorentzian shaped line (see Transition Cross Section):

$$\tau_{ij} = \frac{c^2}{4\pi^2 n^2 \nu^2 (\Delta\nu)\sigma(\nu_o)} \; ,$$

where

$$
\begin{aligned}
c &= \text{velocity of light} \\
\nu &= \text{frequency of the light} \\
n &= \text{refractive index of the material} \\
\Delta\nu &= \text{half-width of the line} \\
\sigma(\nu_o) &= \text{transition cross section at the} \\
& \quad \text{center of the line.}
\end{aligned}
$$

If the observed luminescence lifetime is equal to the calculated natural lifetime, then η_f, the quantum efficiency for fluorescence, is 100%.

PHOTON LUMINESCENCE

In the case of three- and four-level lasers, the quantum efficiency is determined by the lifetimes of the various states. For a three-level laser (see Laser Properties), the <u>non-radiative transition rate</u> S_{32} must be large compared to $\frac{1}{\tau_{31}}$. On the other hand, $\frac{1}{\tau_{21}}$ must be large compared to the non-radiative transition rate S_{21}. For the two transitions combined,

$$\eta = \left(\frac{S_{32}}{S_{32} + \frac{1}{\tau_{31}}}\right) \underbrace{\left(\frac{\frac{1}{\tau_{21}}}{\frac{1}{\tau_{21}} + \omega_{21}}\right)}_{\eta_f}$$

For semiconductor lasers, the quantum efficiency is defined as the number of injected electrons that combine radiatively per injected electron. In the steady state, the number of excited electrons is given by

$$N_2 = \frac{I}{e} \eta\tau,$$

where I is the steady state injected current, e is the electron charge, η is the quantum efficiency, and τ is the electron-hole <u>recombination lifetime</u>.

When the transitions that take place all produce fluorescence, then the term <u>branching ratio</u> is used. The branching ratio is defined as the fraction of all transitions that proceed by a given branch. For example, if ions in energy level 3 can decay to either level 2 or level 1 with the emission of photons (and the radiationless transition rates are negligible), then the branching ratio 3→2 is given by

$$\frac{\frac{1}{\tau_{32}}}{\frac{1}{\tau_{32}} + \frac{1}{\tau_{31}}}.$$

This ratio is analogous to the fluorescent quantum efficiency η_f defined above.

POLARIZATION PROPERTIES

Electromagnetic radiation which exhibits different properties in the different directions at right angles to the direction of propagation is said to be polarized. By convention, the direction of the electric field associated with the electromagnetic radiation is designated as the direction of polarization. The plane of polarization contains the vector representing the electric field and the axis of propagation.

Consider the projection of the electric field vector of an electromagnetic wave on a plane at right angles to the direction of propagation. At any point in the plane, the projection will go through a series of changes, returning to its original value and direction as the wave advances one wavelength. For monochromatic radiation, these changes will be sine or cosine functions of time. As illustrated in Figure 17, the electric vectors will be arranged symmetrically about the direction of propagation for unpolarized light; the tip of the electric vector will oscillate along a line for linearly or plane polarized light; and the tip of the electric vector will rotate around the direction of propagation, following a circular or elliptical path, for circularly or elliptically polarized light, respectively. If the electric vectors are arranged asymmetrically about the direction of propagation, the light is partially polarized. Light is said to be right circularly polarized or left circularly polarized if the sense of rotation of the electric vector, when viewed against the direction of propagation, is clockwise or counterclockwise, respectively. It is often convenient to consider linearly polarized light as made up of a right and a left circularly polarized component.

POLARIZATION PROPERTIES
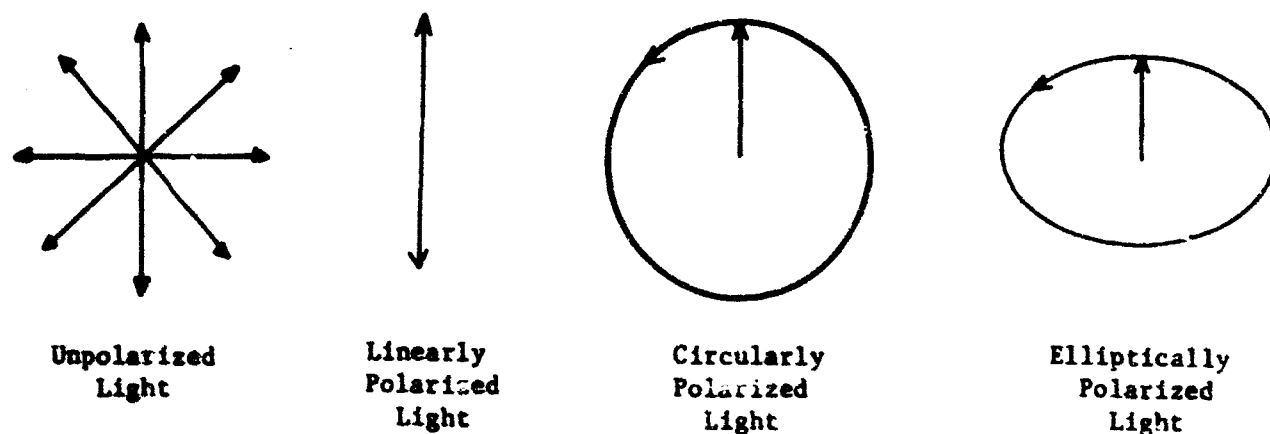
Fig. 17. Polarized light.

The two linear polarized waves which arise in doubly refracting crystals not only exhibit different refractive indices (see Refractive Index), but, in certain substances, the two waves have different absorption coefficients. This phenomenon is known as dichroism (pleochroism). The ratio of the two absorption coefficients is called the dichroic ratio.

Dichroism is exhibited by a number of minerals and by some organic compounds. The best known dichroic mineral is tourmaline, with a dichroic ratio of about 10. Synthetic dichroic materials, such as iodinated polyvinyl alcohol, can be prepared in large sheets, and have dichroic ratios larger than 100.

If unpolarized light is passed through a crystal which exhibits a large dichroic ratio, the exiting light can be almost totally plane polarized. That is, one of the orthogonal linear polarized waves is practically extinguished by absorption, while the other is transmitted in an appreciable amount. Since the absorption coefficients vary with frequency in different ways, if the incident light is linearly polarized, the color of the exiting light will vary with the direction of polarization.

POLARIZATION PROPERTIES

Certain substances cause a rotation of the plane of polarization when plane polarized light is passed through them. This is known as optical activity or circular birefringence. The incident beam can be considered to be resolved into a right circularly polarized beam and a left circularly polarized beam which pass through the substance with different velocities; they then emerge out of phase and recombine to form a plane polarized light beam with its plane rotated from that of the incident beam. If the plane of polarization is rotated clockwise as the observer looks through the material toward the light source, then the substance is dextrorotatory and the rotation is positive; if the plane is rotated counterclockwise, then the substance is levorotatory and the rotation is negative.

Optical activity is shown by crystals, liquids, gases, and solutions. Crystals which are optically active may or may not display such activity when they are melted or in solution. In the case of those which are active only as crystals (e.g., crystalline quartz, but not fused quartz, which is totally inactive), the activity is attributed to a helical distribution of the atoms in the crystal which disappears after melting or dissolving. In the case of those which are always optically active (e.g., many sugars, tartaric acid), the activity is a consequence of an asymmetric molecular structure; one or more carbon or other atoms in a molecule has four different atoms or groups attached to it, and the mirror image of the molecule cannot be superposed on the molecule (just as a right-handed thread cannot be superposed on a left-handed thread). Optical activity is impossible in a centro-symmetrical crystal, but occurs in 15 of the 21 non-centro-symmetric crystal classes; in these it is not possible to superpose the crystal on its mirror image.

The amount of optical rotation, α, of a solution depends on [α], the specific rotatory power of the substance, ℓ, the length of the light path through the substance, and c, the concentration of the substance in a solvent, as follows:

55

POLARIZATION PROPERTIES

$$\alpha = [\alpha]\, \ell \, c \quad ,$$

where ℓ is usually measured in decimeters and c in grams of optically active solute per cubic centimeter of solution. In the case of pure substances, c is absent and $[\alpha]$ is the rotation per unit length, usually expressed in degrees per millimeter for solids. The specific rotatory power varies with the solvent, in the case of a solution, and with the wavelength of the polarized light in the manner

$$[\alpha] = A + B/\lambda^2 \quad ,$$

where A and B are functions of temperature. This variation with wavelength is called rotatory dispersion. As explained above, the optical rotation is attributed to the different velocities of right and left circularly polarized light, and it can be shown that

$$\alpha = \frac{\pi}{\lambda}\,(n_R - n_L)\, \ell \quad ,$$

where n_R and n_L are the refractive indices for right and left circularly polarized light in the substance and ℓ is the length of the light path.

It should be noted that, in crystals, the observation of optical activity is usually complicated by the occurrence of birefringence. For the general case in uniaxial or biaxial crystals (i.e., propagation not along an optic axis), two elliptically polarized waves are transmitted. The two ellipses have the same shape, but they have opposite senses of rotation. The ellipses become circles when the light beam travels along an optic axis.

A substance which absorbs left circularly polarized light differently from right circularly polarized light is said to exhibit circular dichroism. If plane polarized light which is passed through an optically active substance or solution has a wave-

length in the neighborhood of an absorption band, the two circularly polarized components which may be resolved will pass through the substance, not only with different velocities, but with different amplitudes because of the different absorptions. The resulting emergent light beam will then be elliptically polarized rather than plane polarized. The amount of circular dichroism can be calculated from the ellipticity of the polarized light that emerges. The circular dichroism is defined as the difference between the absorption coefficients for left and right circularly polarized light.

In general, when an electromagnetic beam is incident upon a boundary between two media of different refractive indices, part of the beam is reflected and part is refracted. It was noted by Malus that both the reflected and refracted beams are partially plane polarized, and that at a particular angle of incidence the reflected light is completely plane polarized. Brewster established that the tangent of this particular angle of incidence is equal to the ratio of the refractive indices of the two media; this is Brewster's law, and the angle is known as the Brewster angle or the polarizing angle. When the beam is incident at the Brewster angle, the reflected and refracted beams are at right angles to one another (Figure 18). The plane of polarization of the reflected beam is perpendicular to the plane of incidence, and that of the refracted beam is parallel to the plane of incidence.
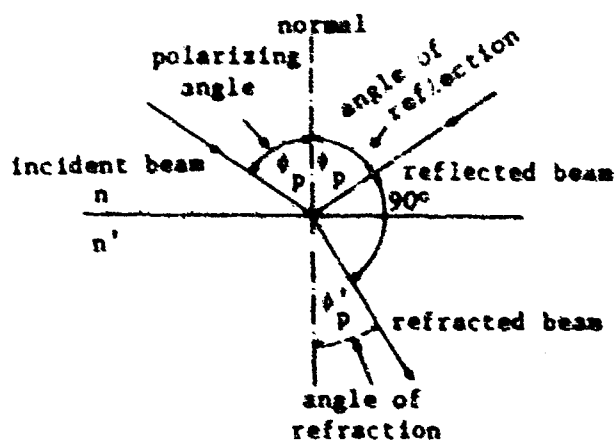
Fig. 18. Brewster's law.

$$\tan \phi_p = n'/n$$

POLARIZATION PROPERTIES

If light incident at the Brewster angle is linearly polarized in the plane of incidence, no light is reflected. If the material has parallel faces, the light is entirely transmitted, as shown in Figure 19; the material becomes a perfect window. Such windows, known as Brewster windows, are used extensively in laser applications.
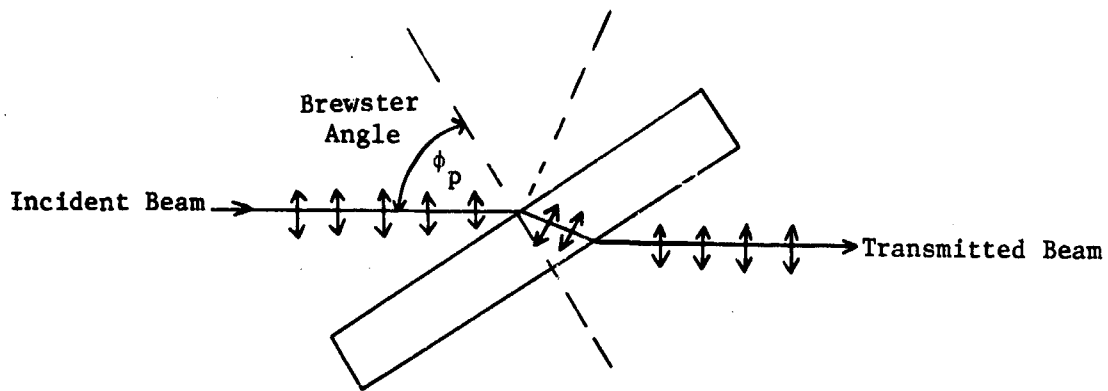
Fig. 19. A Brewster window.

RAMAN EFFECT

The Raman effect, or spontaneous Raman scattering, is a nonlinear, inelastic scattering process in which monochromatic light of frequency ν_o is scattered by molecules of an optically transparent material and new spectral lines of frequency ν_1, ν_2, etc., are formed in the vicinity of the original line. The light scattered elastically has the original frequency ν_o and makes up the Rayleigh line (see Scattering). The altered lines comprise the Raman lines or Raman spectrum, and the differences $\nu_o-\nu_1$, $\nu_o-\nu_2$, etc., may either be positive or negative in sign. The magnitudes of these differences are referred to as Raman frequencies or Raman shifts. If the Raman shift is positive, the corresponding line is called a Stokes line; if the shift is negative, the line is called an anti-Stokes line. The Raman spectrum is characteristic of the molecular species which scattered the incident light, and the Raman shifts are independent of the frequency of the incident light.

The energy change associated with a Raman frequency, for example $h(\nu_o-\nu_1)$, is the energy required to shift the scattering molecule to a different vibrational or rotational energy level. If the energy change is positive (associated with a Stokes line), then the molecule has been raised to a higher energy level from its ground state; if the energy change is negative (associated with an anti-Stokes line), the molecule has dropped from a higher energy level to the ground state and has yielded energy to the scattered light, which then has higher energy than the incident light. Since, at equilibrium, there are more molecules in the ground state than in higher energy levels, the Stokes lines are more intense than the anti-Stokes lines.

Raman scattering is due to the optic vibrations of the scattering medium. Acoustic vibrations can also give rise to Raman-type scattering. This effect is referred to as Brillouin scattering (see Brillouin Effect). In crystals, only optic lattice vibrations (optic phonons) having certain types of symmetry give rise to

59

Raman scattering. Such phonons are said to be Raman active. The phonons of importance have wavelengths very long compared to the lattice constant; Raman shifts thus measure the phonon frequencies at $\vec{k} = 0$.

In the Raman effect, the incident photon as a whole is never absorbed, but rather perturbs the molecule and induces it to undergo a vibrational or rotational transition. Unlike the case of fluorescence, there is no real intermediate state in this process. Furthermore, in the Raman process, absorption and emission together with the simultaneous transition of the molecule from its initial to the final state takes place in one single act of transition. Thus, the Raman process may be distinguished from stepwise transitions involving absorption and emission of photons through two consecutive single quantum transitions via a third molecular energy level. Raman frequencies, when observed by ordinary absorption techniques, lie in the infrared spectral region, whereas in Raman spectroscopy they can be observed in the more convenient visible region. Data obtained by the two methods are not identical, since the two methods involve different mechanisms. Some frequencies observed by Raman spectroscopy are forbidden in infrared absorption spectroscopy, and vice versa, so the two methods are complementary. In solids, a phonon can be simultaneously Raman and infrared active only in crystal structures which lack a center of inversion, i.e., piezoelectric crystals.

The first-order Raman effect is a scattering process in which a single phonon is either created or destroyed. In the second-order Raman effect, two phonons participate in the scattering process. They may both be created (giving a Stokes component in the scattered light), or one may be created and the other destroyed (giving a Stokes or anti-Stokes component), or finally both may be destroyed (giving an anti-Stokes component). There are two types of second-order Raman scattering and they give rise either to a line spectrum or a continuous spectrum. The second-order line

60

spectrum is due to processes in which light has suffered two successive first-order Raman scatterings, and is called iterated Raman scattering; the continuum is due to a scattering process in which light interacts with a pair of phonons in a single event.

If a Raman-active material is exposed to a giant pulse of frequency v_o from a high power Q-switch laser, then light of a different frequency v_1 will be observed, where v_1 corresponds to the most intense Stokes line found in the Raman spectrum of that material. Occasionally there will be observed light corresponding to a second intense Stokes line as well. When the incident laser beam is sufficiently intense to overcome cavity losses at frequency v_1, the resultant stimulated beam at this frequency will be coherent and extremely directional, rather than non-coherent as in the ordinary (spontaneous) Raman effect. This phenomenon is known as the stimulated Raman effect. Along with the first order stimulated Stokes line of frequency v_1 there will appear other lines whose change of frequency from v_o is exactly two (second order), three (third order), or more times the change of the first order line, $v_o - v_1$. That is, the intensity of the first order stimulated Stokes line is high enough to take over the role of the original laser beam and stimulate, in turn, radiation at the second-order Stokes frequency $2v_1 - v_o$. This effect should be carefully distinguished from Stokes lines near these frequencies appearing in the spontaneous Raman emission. These are not equally spaced and their intensity is always very weak. The energy conversion from the incident laser beam to the emitted Stokes lines is much greater than in the case of the spontaneous Raman effect, and may be as high as 20 percent. Under suitable conditions, corresponding stimulated anti-Stokes lines of lower intensity than the Stokes lines are obtained.

Because only one Raman frequency and its multiples are generally observed, the stimulated Raman effect is not useful for obtaining ordinary Raman spectra. However, the stimulated Raman effect serves to change the frequency of the incident laser beam

to a new frequency, and by suitable selection of the incident frequency and the material which will cause the shifting, coherent light of many frequencies becomes available.

A typical Raman spectrum is shown in Figure 20.
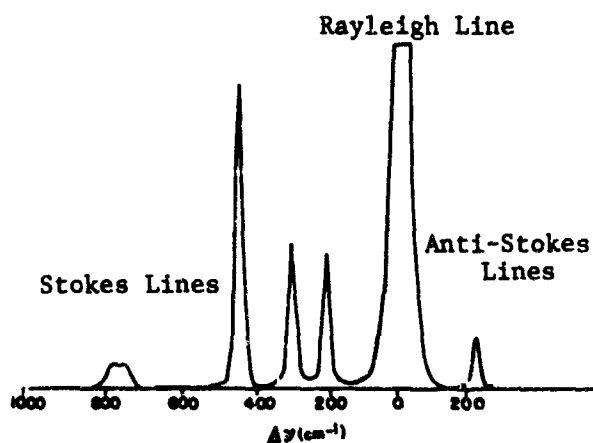
Fig. 20.   Raman spectrum of CCl_4.

REFLECTION COEFFICIENT

An electromagnetic wave falling on the boundary between two media is split into a transmitted and a reflected wave. The reflection coefficient R, or _reflectance_, of the reflecting medium is defined as

$$R = \left| \frac{E_r}{E_i} \right|^2 ,$$

where E_i and E_r are the amplitudes of the electric vectors of the incident and reflected waves, respectively. The sum of the reflectance, transmittance T, and absorptance A of a medium is unity:

$$A + T + R = 1.$$

Reflection of a wave from a smooth surface, so that the direction of propagation is sharply defined after reflection, is known as _specular reflection_. Reflection from a rough surface results in reflected waves travelling in a multitude of directions; such reflection is called _diffuse reflection_. The term _reflectivity_ refers to an intrinsic property of a material; it is equal to the reflectance of a material when that material has an optically smooth surface and is sufficiently thick to be opaque.

The geometrical relationship between the incident, reflected, and transmitted wave at the boundary between two media of refractive indices n_1 and n_2 is shown in Figure 21, where the plane of the paper corresponds to the _plane of incidence_. The plane of incidence is defined as the plane containing both the normal to the reflecting surface and the direction of propagation of the incident wave. For incident

radiation linearly polarized parallel or perpendicular to the plane of incidence, the reflectance is given by

$$R_{\parallel} = \frac{\tan^2(\phi-\phi')}{\tan^2(\phi+\phi')}$$

$$R_{\perp} = \frac{\sin^2(\phi-\phi')}{\sin^2(\phi+\phi')}$$

where ϕ and ϕ' are the angles of incidence and refraction, respectively, as defined in Figure 21.

Incident radiation linearly polarized at an angle θ between the incident electric vector $\vec{E}_i$ and the plane of incidence may be resolved into components parallel and perpendicular to the plane of incidence, and then

$$R = R_{\parallel} \cos^2\theta + R_{\perp} \sin^2\theta.$$

These expressions are called the _Fresnel equations_. Unpolarized light may also be resolved into polarized components parallel and perpendicular to the plane of incidence. Since these two components will be equal, the reflectance for natural light is given by

$$R = \tfrac{1}{2}(R_{\parallel} + R_{\perp})$$

$$= \tfrac{1}{2}\left[\frac{\tan^2(\phi-\phi')}{\tan^2(\phi+\phi')} + \frac{\sin^2(\phi-\phi')}{\sin^2(\phi+\phi')}\right]$$
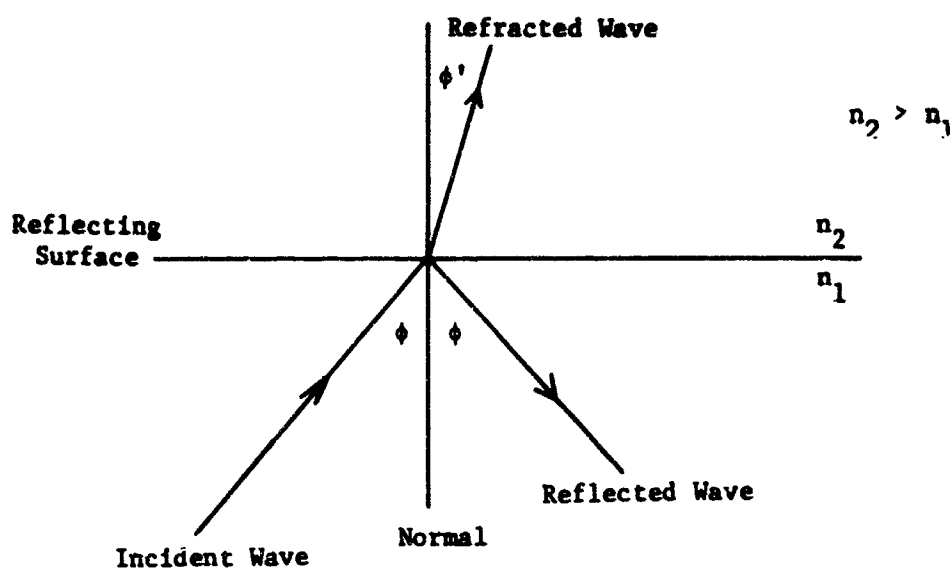
Fig. 21. Reflection at a boundary.

Using the relationship, $\sin\phi/\sin\phi' = n_2/n_1$ (Snell's law), the reflectance of unpolarized light at normal incidence can be expressed as

$$R = \frac{(n_2-n_1)^2}{(n_2+n_1)^2} .$$

When the reflecting medium is absorptive,

$$R = \frac{(n_2-n_1)^2 + k_2^2}{(n_2+n_1)^2 + k_2^2} ,$$

where k_2 is the extinction coefficient of the reflecting medium.

65

REFRACTIVE INDEX

The refractive index, or index of refraction, of a medium is defined as the
ratio of the phase velocity c of electromagnetic radiation in vacuum to the phase
velocity v of the same radiation in the medium:

$$n = \frac{c}{v} .$$

The refractive index is a measure of the refractivity of a medium as measured
by the ratio of the sine of the angle of incidence ϕ to the sine of the angle of
refraction ϕ'. Snell's law states that this ratio is equal to the ratio of the
phase velocities in the two media forming the refracting interface (Figure 22).
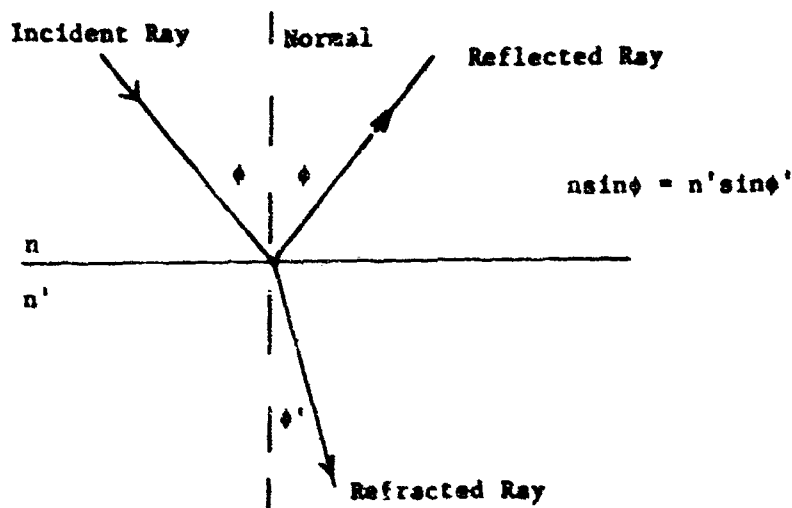
Fig. 22. Snell's law.

Since Maxwell's equations give the phase velocity of a propagating electromag-
netic wave as $v = c/(\epsilon\mu)^{\frac{1}{2}}$, the refractive index is related to the relative permittivity
or dielectric constant ϵ and the relative permeability μ by the equation

$$n = (\epsilon\mu)^{\frac{1}{2}} .$$

REFRACTIVE INDEX

Since the dielectric constant is a function of frequency, the velocity of propagation and the refractive index are also functions of frequency. This phenomenon is known as dispersion.

In non-absorbing media the refractive index is real, while in absorbing media it becomes complex:

$$N = n + i\kappa \ ,$$

where κ is the extinction coefficient. The quantities n and κ are called the optical constants, even though they vary with frequency. The optical constants are related to the electrical parameters of dielectric constant ϵ and electrical conductivity σ, as follows:

$$N = \left(\epsilon\mu + \frac{4\pi\mu\sigma i}{\omega}\right)^{\frac{1}{2}}$$

$$N^2 = (n + i\kappa)^2 = \epsilon\mu + \frac{4\pi\mu\sigma i}{\omega}.$$

Since the real parts on each side of this equation are equal and the imaginary parts are also equal,

$$n^2 - \kappa^2 = \epsilon\mu$$

$$2n\kappa = \frac{4\pi\mu\sigma}{\omega} \ ,$$

where $\omega = 2\pi\nu$ is the angular frequency of the electromagnetic wave in radians/sec.

The absorption coefficient in a medium can be expressed as

$$\alpha = \frac{4\pi n\kappa}{\lambda} = \frac{2n\kappa\omega}{c} \ .$$

68

REFRACTIVE INDEX

The real and imaginary parts of the square of the complex refractive index satisfy the Kramers-Kronig relations, as follows:

$$N^2 = (n + i\kappa)^2 = (n^2 - \kappa^2) + 2n\kappa i$$

$$n^2(\omega) - \kappa^2(\omega) = \frac{2}{\pi} \int_0^\infty \frac{\omega' 2n(\omega')\kappa(\omega')d\omega'}{\omega'^2 - \omega^2} + \text{constant}$$

$$2n(\omega)\kappa(\omega) = \frac{-2\omega}{\pi} \int_0^\infty \frac{[n^2(\omega') - \kappa^2(\omega')]d\omega'}{\omega'^2 - \omega^2}.$$

That is, if the absorption coefficient as a function of frequency is known, both $n(\omega)$ and $\kappa(\omega)$ can be evaluated separately.

If a beam of light enters an optically anisotropic material, it is generally divided into two components which are refracted in different directions. This phenomenon is called birefringence or double refraction. The two components are polarized in two mutually perpendicular planes, and travel at different velocities. In uniaxial crystals (tetragonal, hexagonal and trigonal systems), there is one particular direction, called the optic axis, in which the velocities of the two components are equal. These materials are not doubly refracting along the optic axis, which coincides in direction with the principal crystallographic axis. In other directions, one component, the ordinary wave, travels with a velocity independent of the direction of propagation; it is polarized with its electric field vector perpendicular to the plane containing the optic axis and the direction of propagation. The other component, the extraordinary wave, travels with a velocity which depends on the relation between its direction and the optic axis; it is polarized with its electric field vector parallel to the plane containing the optic axis and the direction of propagation. That is, a doubly refracting material has one refractive index (n_o) for the ordinary wave and another (n_e) for the extraordinary wave. The latter index does not have a unique value, since the velocity of the extraordinary wave is different in different

69

directions. It is customary, however, to specify the extraordinary refractive index
for a direction perpendicular to the optic axis. As shown in Figure 23, Snell's law
does not hold for the extraordinary wave; for incident light normal to the surface,
the extraordinary wave will be refracted at some angle that is not zero.
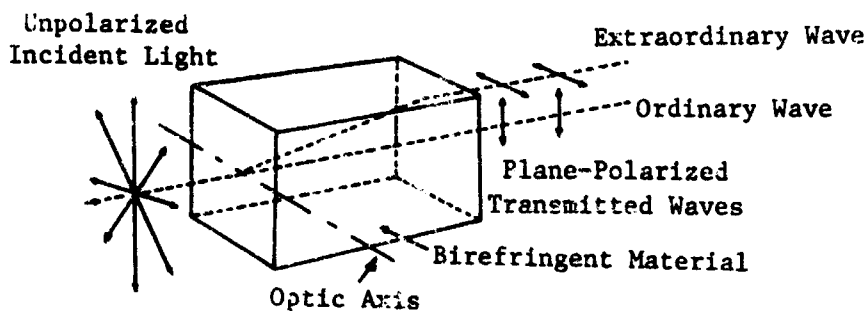
Fig. 23. Unpolarized light is split into two beams polarized at
right angles by an uniaxial birefringent material.

Some materials (e.g., calcite) exhibit negative birefringence, in which the re-
fractive index for the ordinary wave is greater than that for the extraordinary wave.
A crystal is said to be positive uniaxial when $(n_e - n_o)$ is positive, and negative
uniaxial when $(n_e - n_o)$ is negative.

In biaxial crystals (triclinic, monoclinic and orthorhombic systems), there are
two directions in which the velocities of the two components of a beam of light are
equal, and double refraction does not take place; these are the optic axes, and the
angle between them is the optic angle. In other directions, the two components have
different velocities, and the velocities of both depend on the relation between the
direction of propagation and the optic axes; both components are thus extraordinary
waves. In these crystals there are three principal refractive indices (n_x, n_y, n_z),
which are measured in directions at right angles to each other. These indices are
selected so that $n_x < n_y < n_z$. Positive biaxial crystals have the value of n_y closer
to that of n_x than to n_z, whereas negative biaxial crystals have the value of n_y closer

to that of n_z than to n_x.

Isotropic crystals (cubic system) are of course not doubly refracting and have only one refractive index.

The optical properties of a crystal are often described in terms of its __index ellipsoid__ or __indicatrix__. The index ellipsoid has the following important property: a plane passed through the center of the ellipsoid at right angles to the direction of propagation of an electromagnetic wave will cut the ellipsoid in an ellipse whose semi-axes are the two refractive indices associated with the two possible components of the wave, plane polarized along these semi-axes. The equation of the index ellipsoid is given by

$$\frac{x^2}{n_x{}^2} + \frac{y^2}{n_y{}^2} + \frac{z^2}{n_z{}^2} = 1 \quad ,$$

where n_x, n_y, and n_z are the principal refractive indices. The equation of the index ellipsoid in a uniaxial crystal is given by (Figure 24).

$$\frac{x^2+y^2}{n_o{}^2} + \frac{z^2}{n_e{}^2} = 1.$$
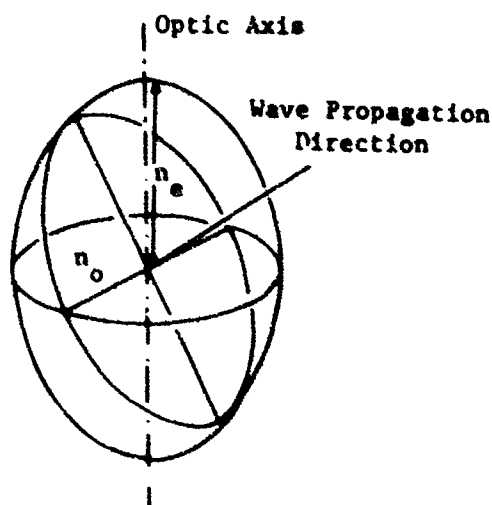
Fig. 24. The index ellipsoid for a (positive) uniaxial crystal.

REFRACTIVE INDEX

Consider a beam of linearly polarized light propagating perpendicular to the optic axis of a doubly refracting crystal and with its plane of polarization making an angle of 45 degrees with the optic axis. Although the ordinary and extraordinary waves in the crystal will be of equal magnitude, they will travel with different velocities. The phase difference between them as they leave the crystal will depend on the difference between the refractive indices n_o and n_e as well as on the length of the light path ℓ through the material:

$$\Gamma = \frac{2\pi\ell}{\lambda} \; (n_e - n_o) \;,$$

where the _phase retardation_ or _optical phase shift_ Γ is expressed in radians and λ is the wavelength of the light in vacuum. If the refractive indices and the thickness of the crystal is such that $\Gamma = \pi/2$ radians, the crystal is known as a _quarter-wave plate_. Similarly, if $\Gamma = \pi$, the crystal is a _half-wave plate_. The emerging light will be circularly polarized in the case of a quarter-wave plate and plane polarized, with the plane of polarization rotated by 90°, in the case of a half-wave plate (Figure 25).
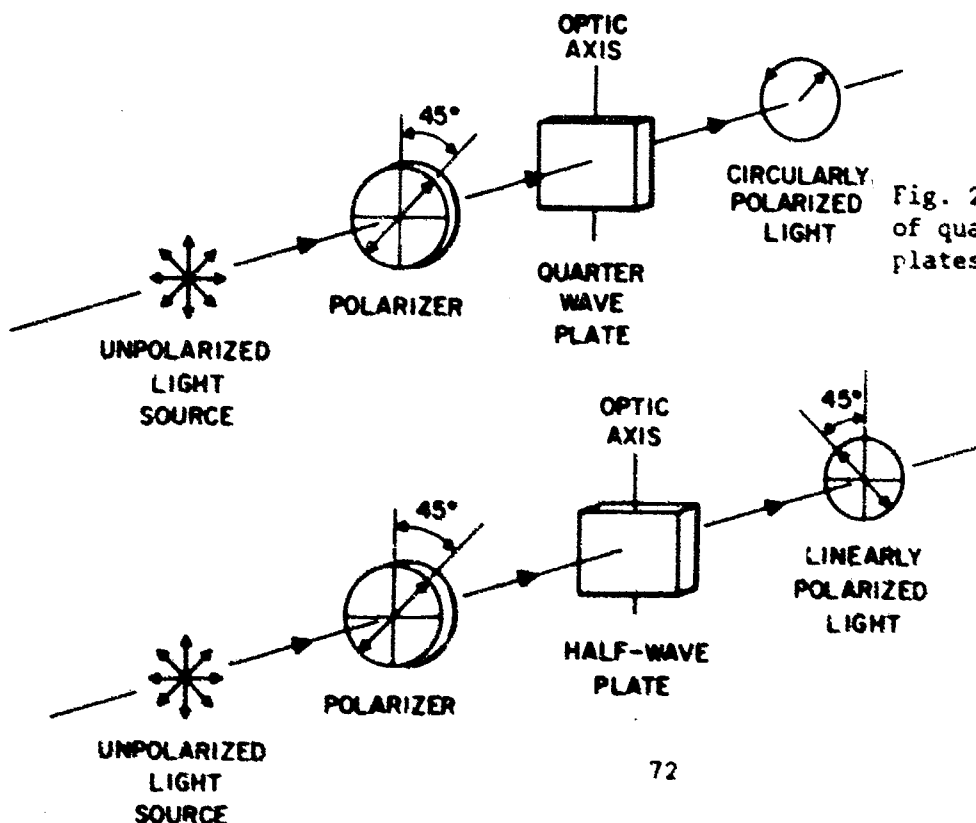
Fig. 25. Polarizing properties of quarter-wave and half-wave plates.

SCATTERING

When a light beam passes through a medium its intensity is decreased by reflection at the surfaces, absorption, and scattering. Scattering of a portion of the light beam is caused by the presence of particles of varying size, from microscopic bits to atoms and electrons, in the path of the light beam; the interaction of the photons with the particles causes deflection of the photons in all directions. Scattering is often easily visible in a heterogeneous medium, whereas scattering in a homogeneous medium is much less noticeable.

When the radius of the particles which cause the scattering is much greater than the wavelength of the light beam (Tyndall effect), the scattered energy is nearly independent of the wavelength. When the particle radius and wavelength are about the same, the scattered energy reaches a maximum (Figure 26). As the particle radius becomes smaller than the wavelength, the scattered energy decreases, and when the radius is yet smaller (Rayleigh scattering) the scattered energy is inversely proportional to the fourth power of the wavelength. Because of this inverse fourth power relationship, blue light, with a smaller wavelength, is scattered more than red light. This explains why the sky is blue, even though sunlight is somewhat weaker in the blue portion of the spectrum than in the red portion.
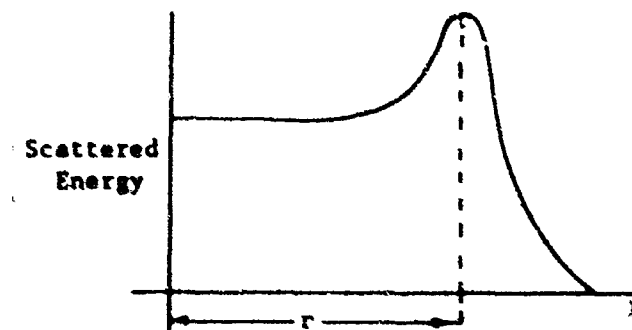
Fig. 26. Typical relation between energy scattered and wavelength for particles of radius r.

SCATTERING

In Rayleigh scattering, if the light beam encounters particles which absorb strongly, the scattering will no longer be inversely proportional to the fourth power of the wavelength. The intensity of the light scattered at an angle θ with the incident light beam is directly proportional to the factor $(1 + \cos^2 \theta)$. Rayleigh scattering is a coherent scattering, in that there are definite phase relations between the original light beam and the scattered light beam. Interference occurs between the light beams scattered by two or more centers. The scattered light beams are at least partially plane-polarized, with the maximum polarization at $\theta = 90°$.

If only scattering is involved in the attenuation of the light beam passing through a medium, then a __scattering coefficient__ α can be calculated by the formula

$$I = I_o \, e^{-\alpha \ell}$$

where I_o is the original intensity of the light beam and I is its intensity after passing through a distance ℓ of the material.

Certain substances show an intense scattering, called __critical scattering__, in the neighborhood of the liquid-gas critical point. At this point the gas will strongly scatter all light and will have a striking opalescent appearance. This intense scattering is a result of the large fluctuation of the density (and the refractive index) throughout the gas sample under the conditions of the critical point.

TRANSITION CROSS SECTION

The cross section of a transition represents a normalized radiation transition probability; it is the equivalent geometrical area (or size) of an ion for absorption or emission of radiation, and is measured in square centimeters or barns (1 barn = 10^{-24} cm^2).

Consider a two-energy-level atomic system with an atomic density N_2 in the upper excited level at energy E_2 and a density N_1 in the lower level E_1. Radiation of a proper frequency ν will cause transitions to occur between these two energy levels, where

$$h\nu = E_2 - E_1.$$

There exist three types of transition processes by which equilibrium establishes itself in this system, as illustrated in Figure 27:

1. Spontaneous emission described by A_{21}, the probability per unit time that an atom in a state at E_2 will make a transition to a state at E_1 without any outside influence. No electromagnetic field is required.

2. Stimulated emission from E_2 to E_1. This process occurs with a transition probability per atom per unit time W_{21}, where W_{21} depends on the density of photons around the atom.

3. Absorption of a photon with subsequent transition of the atom from E_1 to E_2 occuring with a probability per unit atom per unit time W_{12}, where W_{12} depends on the density of photons around the atom.

The "probability" W_{ij} is referred to as an induced emission rate and is expressed in units of sec^{-1}.

TRANSITION CROSS SECTION

| Absorption | Stimulated Emission | Spontaneous Emission |
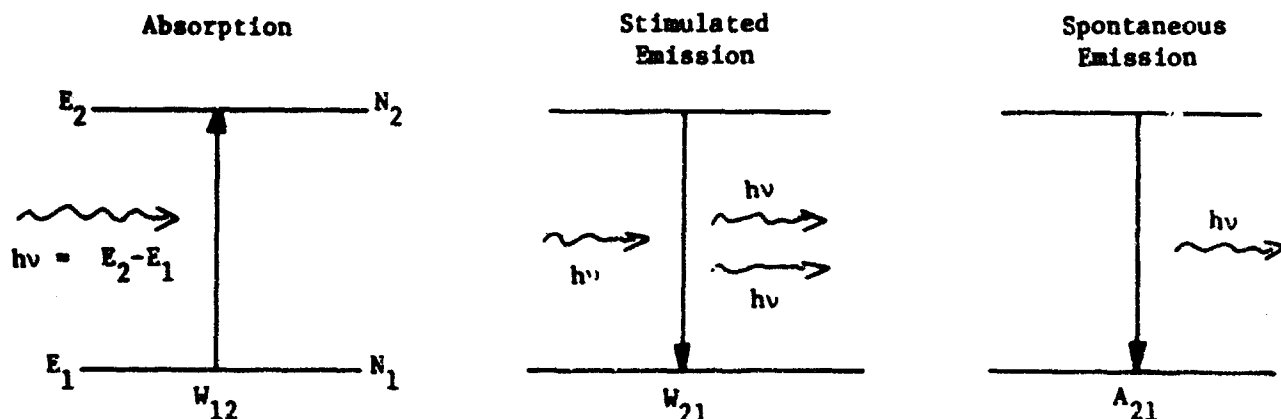
Fig. 27. Transition processes

The frequently defined <u>Einstein transition probabilities</u> are A_{21}, B_{21}, and B_{12}, where

$$W_{12} = B_{12}\rho(\nu) \quad \text{and} \quad W_{21} = B_{21}\rho(\nu).$$

Here, $\rho(\nu)$ is the frequency dependent radiation energy density per unit frequency interval. The Einstein B coefficient is expressed in units of cm^3/erg-sec. The Einstein A coefficient may be expressed as

$$A_{21} = \frac{8\pi h\nu^3}{c^3} B_{21}$$

$$\text{or} \quad A_{21} = \frac{1}{\tau_{21}},$$

where τ_{21} is the radiative or natural lifetime of energy level 2 (see Photon Luminescence) and c is the velocity of light in a vacuum. In a material with index of refraction n,

$$A_{21} = \frac{8\pi h\nu^3 n^3}{c^3} B_{21}.$$

Then

$$W_{21} = \frac{\rho(\nu)c^3}{8\pi h\nu^3 n^3 \tau_{21}}.$$

76

TRANSITION CROSS SECTION

The above discussion implicitly assumes that $\rho(\nu)$ is a constant over the frequency range in which the atoms can emit or absorb energy. In a laser, however, the emitted energies of interest occur in a narrow band of frequencies which is small in comparison to the atomic absorption bandwidth. A more useful expression for the transition rate induced by a monochromatic beam is given by

$$W_{21} = \frac{c^2 I_\nu}{8\pi h \nu^3 n^3 \tau_{21}} f(\nu) ,$$

where I_ν is the energy flux of the beam in erg/sec-cm^2 and $f(\nu)$ is the <u>atomic line shape</u> function normalized such that

$$\int_0^\infty f(\nu) d\nu = 1.$$

That is, the line shape function is defined such that $f(\nu)d\nu$ is the probability that a given transition will result in an emission or absorption of a photon with energy between $h\nu$ and $h(\nu+d\nu)$.

If the photon flux incident on a material is n_p photons per sec-cm^2, the induced transition rate per atom is given by

$$W_{12} = n_p \sigma_{12} \quad \text{and} \quad W_{21} = n_p \sigma_{21} ,$$

where σ_{12} represents the cross section for the transition from energy level 1 to energy level 2, and σ_{21} the cross section for the transition from energy level 2 to energy level 1. If the simplifying assumption is made that the respective degeneracies of the levels 1 and 2 are equal, then

$$W_{12} = W_{21}$$

and

$$\sigma_{12} = \sigma_{21} = \sigma.$$

TRANSITION CROSS SECTION

The net absorption coefficient α is given by the number of absorbing transitions, minus the number of stimulated emission transitions, as follows:

$$\alpha = (N_1\sigma_{12} - N_2\sigma_{21}) = (N_1-N_2)\sigma.$$

Here, spontaneous emission has been neglected. The useful parameter for laser action is the W probability; radiation emitted by stimulation is coherent and will reinforce the laser beam while the radiation emitted spontaneously does not contribute significantly to the beam.

The transition cross section is related to the frequency ν as follows:

$$\sigma(\nu) = \frac{c^2}{8\pi\nu^2 n^2 \tau_{21}} f(\nu).$$

for a <u>Gaussian</u> shaped line (e.g., Doppler broadening in gases or thermal broadening of ion levels in crystals,

$$\sigma_{gauss}(\nu) = \left(\frac{\log_e}{\pi}\right)^{1/2} \frac{c^2}{4\pi\nu^2 n^2 (\Delta\nu)\tau_{21}} \exp\left\{-4\log_e 2 \left(\frac{\nu - \nu_0}{\Delta\nu}\right)^2\right\}.$$

For a <u>Lorentzian</u> shaped line (e.g., natural lifetime broadening)

$$\sigma_{lorentzian}(\nu) = \frac{c^2}{4\pi^2 n^2 \nu^2 (\Delta\nu)\tau_{21}} \left\{\frac{1}{1 + \left(\frac{\nu - \nu_0}{\Delta\nu/2}\right)^2}\right\},$$

where
- τ_{21} = the radiative or natural lifetime of level 2
- c = the velocity of light
- n = refractive index of the material
- $(\Delta\nu)$ = the width of the line at half maximum absorption (see Absorption)
- ν_0 = center of the absorption line

TRANSITION CROSS SECTION

A useful parameter is the atomic line shape function at the center of the line, $f(\nu_o)$:

$$f(\nu_o) \; = \; \frac{2}{\Delta\nu} \left(\frac{\log_e 2}{\pi} \right)^{\frac{1}{2}} \quad \text{for a Gaussian line} \quad ,$$

and

$$f(\nu_o) \; = \; \frac{2}{\pi\Delta\nu} \quad \text{for a Lorentzian line.}$$

PROPERTIES CROSS REFERENCES

Absorptance
  See ABSORPTION

ABSORPTION
  Absorptance
  Absorption Coefficient
  Absorption Edge
  Absorption Line
  Absorption Spectrum
  Absorptivity
  Direct Transition
  Exciton Absorption
  EXTINCTION COEFFICIENT
  Fundamental Absorption Edge
  Indirect Transition
  Lambert's Law
  Linewidth
  Negative Absorption
  Total Absorption Coefficient
  Transition Cross Section
  Transmissivity
  TRANSMITTANCE

Absorption Coefficient
  See ABSORPTION

Absorption Edge
  See ABSORPTION

Absorption Line
  See ABSORPTICN

Absorption Spectrum
  See ABSORPTION

Absorptivity
  See ABSORPTION

Anti-Stokes Line
  See BRILLOUIN EFFECT
      RAMAN EFFECT

Atomic Line Shape
  See Transition Cross Section

Beamwidth
  See LASER PROPERTIES

Biaxial
  See REFRACTIVE INDEX

BIREFRINGENCE
  See REFRACTIVE INDEX

Blackbody
  See PHOTON EMISSIVITY

Branching Ratio
  See PHOTON LUMINESCENCE

Brewster Angle
  See POLARIZATION PROPERTIES

Brewster's Law
  See POLARIZATION PROPERTIES

Brewster Window
  See POLARIZATION PROPERTIES

BRILLOUIN EFFECT
  Anti-Stokes Line
  Brillouin Shift
  Doppler Component
  Rayleigh Line
  Spontaneous Brillouin Scattering
  STIMULATED BRILLOUIN EFFECT
  Stokes Line

Brillouin Shift
  See BRILLOUIN EFFECT

Cavity Decay Time
  See LASER PROPERTIES

Cavity Modes
  See LASER PROPERTIES

Circular Birefringence
  See POLARIZATION PROPERTIES

Circular Dichroism
  See POLARIZATION PROPERTIES

Circularly Polarized Light
  See POLARIZATION PROPERTIES

Clamped Electro-optic Coefficients
  See ELECTRO-OPTIC EFFECT

Coherence Distance
  See NONLINEAR OPTICAL EFFECTS

FARADAY EFFECT
  Faraday Configuration
  Free-carrier Faraday Effect
  Interband Faraday Effect
  Inverse Faraday Effect
  Kundt Constant
  Magneto-optic Rotation
  Verdet Constant

Ferromagnetic Faraday Effect
  See KERR MAGNETO-OPTIC EFFECT

Fluorescence
  See PHOTON LUMINESCENCE

Fluorescence Lifetime
  See PHOTON LUMINESCENCE

Fluorescent Quantum Efficiency
  See PHOTON LUMINESCENCE

Four Level Laser
  See LASER PROPERTIES

Free-Carrier Faraday Effect
  See FARADAY EFFECT

Fresnel Equations
  See REFLECTION COEFFICIENT

Fundamental Absorption Edge
  See ABSORPTION

Gain
  See LASER PROPERTIES

Gaussian Line
  See Transition Cross Section

Half-wave Plate
  See REFRACTIVE INDEX

Half-wave Voltage
  See ELECTRO-OPTIC EFFECT

Hemispherical Emittance
  See PHOTON EMISSIVITY

Idler Beam
  See NONLINEAR OPTICAL EFFECTS

Impermeability Coefficients
  See ELECTRO-OPTIC EFFECT

Incoherent
  See LASER PROPERTIES

Index Ellipsoid
  See REFRACTIVE INDEX

Index Matching
  See NONLINEAR OPTICAL EFFECTS

Index Matching Angle
  See NONLINEAR OPTICAL EFFECTS

Index of Refraction
  See REFRACTIVE INDEX

Indicatrix
  See REFRACTIVE INDEX

Indirect Transition
  See ABSORPTION

Induced Emission Rate
  See Transition Cross Section

Injection Laser Diode
  See LASER PROPERTIES

Intensity Modulation
  See ELECTRO-OPTIC EFFECT

Interband Faraday Effect
  See FARADAY EFFECT

Inverse Faraday Effect
  See FARADAY EFFECT

Isoclinic Line
  See PHOTOELASTIC EFFECT

Iterated Raman Scattering
  See RAMAN EFFECT

Kerr Cell
  See ELECTRO-OPTIC EFFECT

Kerr Constant
  See ELECTRO-OPTIC EFFECT

KERR EFFECT
  See ELECTRO-OPTIC EFFECT

KERR MAGNETO-OPTIC EFFECT
 Ferromagnetic Faraday Effect
 Polar Kerr Magneto-optic Effect

Kirchoff's Radiation Law
 See PHOTON EMISSIVITY

Kramers-Kronig Relations
 See REFRACTIVE INDEX

Kundt Constant
 See FARADAY EFFECT

Lambert's Cosine Emission Law
 See PHOTON EMISSIVITY

Lambert's Law
 See ABSORPTION

LASER OUTPUT WAVELENGTH
 See LASER PROPERTIES

LASER PROPERTIES
 Beamwidth
 Cavity Decay Time
 Cavity Modes
 Coherence Length
 Coherence Time
 Coherent
 Fabry-Perot Etalon
 Fabry-Perot Interferometer
 Four Level Laser
 Gain
 Incoherent
 Injection Laser Diode
 LASER OUTPUT WAVELENGTH
 Metastable State
 Non-radiative Transition
 Optical Maser
 Optical Pumping
 Oscillation Threshold
 Population Inversion
 Pump Band
 Q-Spoiling
 Q-Switching
 Quality Factor
 Rate Equations
 Spatial Coherence

LASER PROPERTIES (Cont'd)
 Stimulated Emission Rate
 Three Level Laser

Levorotatory
 See POLARIZATION PROPERTIES

Lifetime
 See PHOTON LUMINESCENCE

Linewidth
 See ABSORPTION

Linear Electro-optic Coefficients
 See ELECTRO-OPTIC EFFECT

Linearly Polarized Light
 See POLARIZATION PROPERTIES

Lorentzian Line
 See Transition Cross Section

Luminescence
 See PHOTON LUMINESCENCE

LUMINESCENCE LIFETIME
 See PHOTON LUMINESCENCE

Magnetic Double Refraction
 See COTTON-MOUTON EFFECT

Magneto-optic Rotation
 See FARADAY EFFECT

Metastable State
 See LASER PROPERTIES

Natural Lifetime
 See PHOTON LUMINESCENCE

Negative Absorption
 See ABSORPTION

Negative Biaxial
 See REFRACTIVE INDEX

Negative Birefringence
 See REFRACTIVE INDEX

Negative Uniaxial
 See REFRACTIVE INDEX

85

PHOTON EMISSIVITY (Cont'd)
  Radiance
  Radiant Emittance
  Spectral Emissivity
  Spectral Emittance
  Spectral Radiant Emittance
  Stefan-Boltzmann Law
  Total Emittance
  Wien's Distribution Law

PHOTON LUMINESCENCE
  Branching Ratio
  Fluorescence
  Fluorescence Lifetime
  Fluorescent Quantum Efficiency
  Lifetime
  Luminescence
  LUMINESCENCE LIFETIME
  Natural Lifetime
  Non-radiative Transition Rate
  Phosphorescence
  Phosphors
  QUANTUM EFFICIENCY
  Quantum Yield
  Radiative Lifetime
  RECOMBINATION LIFETIME
  Spontaneous Emission Lifetime
  Spontaneous Emission Rate
  Stokes' Law
  Stokes Shift

Piezo-optic Coefficients
  See PHOTOELASTIC EFFECT

Plank's Distribution Law
  See PHOTON EMISSIVITY

Plane of Incidence
  See REFLECTION COEFFICIENT

Plane of Polarization
  See POLARIZATION PROPERTIES

Plane Polarized Light
  See POLARIZATION PROPERTIES

Pleochroism
  See POLARIZATION PROPERTIES

POCKELS EFFECT
  See ELECTRO-OPTIC EFFECT

POLARIZATION PROPERTIES
  Brewster Angle
  Brewster's Law
  Brewster Window
  Circular Birefringence
  Circular Dichroism
  Circularly Polarized Light
  Dextrorotatory
  Dichroic Ratio
  Dichroism
  Elliptically Polarized Light
  Levorotatory
  Linearly Polarized Light
  Optical Activity
  Optical Rotation
  Partially Polarized Light
  Plane of Polarization
  Plane Polarized Light
  Pleochroism
  Polarizing Angle
  Rotatory Dispersion
  Specific Rotatory Power
  Unpolarized Light

Polarizing Angle
  See POLARIZATION PROPERTIES

Polar Kerr Magneto-optic Effect
  See KERR MAGNETO-OPTIC EFFECT

Population Inversion
  See LASER PROPERTIES

Positive Biaxial
  See REFRACTIVE INDEX

Positive Uniaxial
  See REFRACTIVE INDEX

Principal Refractive Indices
  See REFRACTIVE INDEX

Pump Band
  See LASER PROPERTIES

Q-Spoiling
  See LASER PROPERTIES

Q-Switching
  See LASER PROPERTIES

REFRACTIVE INDEX (Cont'd)
  Refractivity
  Snell's Law
  Uniaxial

Refractivity
  See REFRACTIVE INDEX

Rotatory Dispersion
  See POLARIZATION PROPERTIES

SCATTERING
  Critical Scattering
  Rayleigh Scattering
  Scattering Coefficient
  Tyndall Effect

Scattering Coefficient
  See SCATTERING

Second Harmonic Generation
  See NONLINEAR OPTICAL EFFECTS

Second-order Polarization Tensor
  See NONLINEAR OPTICAL EFFECTS

Second-order Raman Effect
  See RAMAN EFFECT

Snell's Law
  See REFRACTIVE INDEX

Spatial Coherence
  See LASER PROPERTIES

Specific Rotatory Power
  See POLARIZATION PROPERTIES

Spectral Emissivity
  See PHOTON EMISSIVITY

Spectral Emittance
  See PHOTON EMISSIVITY

Spectral Radiant Emittance
  See PHOTON EMISSIVITY

Specular Reflection
  See REFLECTION COEFFICIENT

Spontaneous Brillouin Scattering
  See BRILLOUIN EFFECT

Spontaneous Emission
  See Transition Cross Section

Spontaneous Emission Lifetime
  See PHOTON LUMINESCENCE

Spontaneous Emission Rate
  See PHOTON LUMINESCENCE

Spontaneous Raman Scattering
  See RAMAN EFFECT

Stefan-Boltzmann Law
  See PHOTON EMISSIVITY

STIMULATED BRILLOUIN EFFECT
  See BRILLOUIN EFFECT

Stimulated Emission
  See Transition Cross Section

Stimulated Emission Rate
  See LASER PROPERTIES

STIMULATED RAMAN EFFECT
  See RAMAN EFFECT

Stokes' Law
  See PHOTON LUMINESCENCE

Stokes Line
  See BRILLOUIN EFFECT
      RAMAN EFFECT

Stokes Shift
  See PHOTON LUMINESCENCE

Strain-optic Coefficients
  See PHOTOELASTIC EFFECT

Stress Birefringence
  See PHOTOELASTIC EFFECT

Stress-optic Coefficients
  See PHOTOELASTIC EFFECT

Synchronism Direction
  See NONLINEAR OPTICAL EFFECTS

Three Level Laser
  See LASER PROPERTIES

Total Absorption Coefficient
  See ABSORPTION

Total Emittance
  See PHOTON EMISSIVITY

Transition Cross Section
  See ABSORPTION
  Atomic Line Shape
  Einstein Transition Probabilities
  Gaussian Line
  Induced Emission Rate
  Lorentzian Line
  Spontaneous Emission
  Stimulated Emission

Transmissivity
  See ABSORPTION

TRANSMITTANCE
  See ABSORPTION

Tyndall Effect
  See SCATTERING

Unclamped Electro-optic Coefficients
  See ELECTRO-OPTIC EFFECT

Uniaxial
  See REFRACTIVE INDEX

Unpolarized Light
  See POLARIZATION PROPERTIES

Verdet Constant
  See FARADAY EFFECT

Voigt Configuration
  See COTTON-MOUTON EFFECT

Voigt Effect
  See COTTON-MOUTON EFFECT

Wien's Distribution Law
  See PHOTON EMISSIVITY

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Hughes Aircraft Company Culver City, California 90230	Unclassified
	2b. GROUP

3. REPORT TITLE

GLOSSARY OF OPTICAL PROPERTIES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Glossary

5. AUTHOR(S) (First name, middle initial, last name)

Richard I. Akawie
Sheldon J. Welles
Irnee J. D'Haenens

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1969	89	0

8a. CONTRACT OR GRANT NO. F33615-68-C-1225	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 7381 and 8975	
c. Task No. 738103 and 897503	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) S-10
d.	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Air Force Materials Laboratory Air Force Systems Command Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

A glossary of optical property indexing terms used by the Electronic Property Information Center is presented. Twenty eight primary optical property descriptors and over 180 related terms are carefully defined. A detailed list of property cross references provides a complete index to the glossary.

DD FORM 1473 (1 NOV 65)

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Optical Properties						
Electro-optic Properties						
Magneto-optic Properties						
Laser Properties						